CHAPTER 8

Climate Change Impacts and Adaptation in Florida's Agriculture

Young Gu Her[1], Kenneth J. Boote[2], Kati W. Migliaccio[3], Clyde Fraisse[3], David Letson[4], Odemari Mbuya[5], Aavudai Anandhi[6], Hongmei Chi[7], Lucy Ngatia[5], and Senthold Asseng[3]

[1]Agricultural and Biological Engineering Department / Tropical Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Homestead, FL; [2]Agronomy Department / Agricultural and Biological Engineering Department, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL; [3]Agricultural and Biological Engineering Department, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL; [4]Marine Ecosystems and Society Department, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL; [5]Center for Water and Air Quality, College of Agriculture and Food Sciences, Florida Agricultural and Mechanical University, Tallahassee, FL; [6]Biological Systems Engineering Department / Center for Water and Air Quality, College of Agricultural and Food Sciences, Florida Agricultural and Mechanical University, Tallahassee, FL; [7]Computer and Information Sciences Department, College of Science and Technology, Florida Agricultural and Mechanical University, Tallahassee, FL

In this chapter, we describe Florida's agriculture, the vulnerability of its crops and livestock to climate change and possible adaptation strategies. Much of Florida's agricultural success is linked to its moderate climate, which allows vegetable and fruit crop production during the winter/spring season as well as the production of perennial crops such as citrus and sugarcane. In addition, there is a substantial livestock industry that uses the extensive perennial grasslands. While rising CO2 is generally beneficial to crop production but detrimental to nutritional quality, increase in temperature will cause mostly negative effects on yield. Florida's agriculture faces additional challenges from climate change characterized by sea level rise and intensified extreme climate events, affecting land and irrigation water availability, livestock productivity and pest and disease pressure. New technologies and adaptation strategies are needed for sustainable agricultural production in Florida, including increased water and nutrient use efficiency in crops, crop and livestock breeding for heat stress, pest and disease resistance and reduced exposure of livestock to high temperature. Irrigation is a favored adaptation, but places an even greater burden or potential conflict between agriculture and community use of water resources.

Key Messages

- Florida's agricultural industries provide over $120 billion in economic revenue to the state, second only to tourism, and support more than two million jobs.
- Florida's diverse climate conditions make it suitable for many crops, fruits, livestock, and seafood, although these are vulnerable to climate variations that occur from year to year.
- Florida's agriculture has a long history of successful adaptations to the vagaries of weather and climate, but climate change poses a challenge that is unprecedented in magnitude and rates of change.
- Although current temperatures are near optimal for growing many of our crops, yields are lower during the hotter seasons that occur now, and additional increases in future temperatures will lead to lower crop yields, creating challenges to the competitiveness of current production systems.
- Florida's agriculture faces additional challenges from climate change characterized by sea level rise and intensified extreme climate events, affecting land and irrigation water

availability, crop yield and quality, livestock productivity, as well as pest and disease pressures.
- The known increases in atmospheric CO_2 concentration can stimulate growth in some crops but will reduce the nutritional value of many food crops. Higher atmospheric CO_2 concentration will also increase canopy temperatures and could add to the adverse effects of temperature.
- New technologies and adaptation strategies needed for sustainable agricultural production in Florida include increased water and nutrient use efficiency in crops, crop and livestock breeding for heat stress, pest and disease resistance, and reduced exposure of livestock to high temperatures.
- Knowledge gaps include an understanding of climate change impacts on growth and nutritional value of vegetable and fruit crops, the dynamics of pests and diseases, and direct and indirect effects (the latter via pasture growth) on livestock and livestock-crop systems.
- New experiments and development of modeling and analysis tools are needed for many of the economically-important agricultural systems in order to better estimate climate change impacts on Florida's diverse agricultural production systems.

Keywords

Florida's agriculture; Climate change; Crops; Fruits; Livestock; Sea level rise; Irrigation; Water resources; Elevated carbon dioxide; Increased air temperature; Rainfall change; Salt water intrusion; Salinity; Climate change adaptation; Cover crop; Conservation tillage; Sod-based rotation; Plastic mulch; Drought tolerant crops; Heat tolerant corps, Drought tolerant forage; Heat tolerant livestock; Livestock facility renovation; Livestock genomic selection; Mixed crop-livestock systems; Decision support systems; Crop modeling

Introduction

Florida is one of the largest crop producers in the United States. The state's agricultural industries contribute over \$120 billion to the economic revenue of the state (Putnam 2015a) and the annual market value of Florida's crop products is \$7.8 billion (Putnam 2015c). In fact, agricultural products from Florida have increased in export value by about \$2 billion US dollars between 2004 and 2014; the state of Florida ranked eighth in the US, with \$4 billion in agricultural exports in 2014 (Sleep and Gitzen 2015). The largest importers of Florida products are Canada, Bahamas, The Netherlands, Dominican Republic, Mexico and Colombia (Sleep and Gitzen 2015). Export products from Florida include meat products, orange juice, grapefruit juice, fruits, and nuts. Hence, Florida significantly contributes to the local, regional and global food supply via fresh market vegetables and fruits (Putnam 2015c); and the effects of climate change on agricultural yields, nutritional value and prices in Florida as well as follow-on impacts on food processing, storage, transportation and retailing have implications for food security beyond the state's borders.

Agricultural trends in terms of land area and agricultural products sold have changed in Florida since the 1960s, with the market value of agricultural products increasing and the area of farmland decreasing. The number of farms has increased over this same period, with the average farm size being 81 ha (200 acres) in 2015 (Putnam 2015b). The number of farms in Florida has increased from 44,000 in 2002 to 47,300 in 2015, supporting two million full- and part-time jobs (Putnam 2015b, Putnam 2015c, Sleep and Gitzen 2015).

Florida's agriculture is a major consumer of water. Surface and groundwater fed by rainfall is the main source of irrigation for growing crops, and about 12.1 billion liters (3.2 billion gallons) per day of Florida's water resources are used to grow crops (Marella 1999).

The Florida peninsula covers six degrees of latitude between approximately 25° N and 31° N, with a range of climatic regions from Tallahassee to Key West characterized by differences in frost occurrence, chill accumulation, growing degree accumulation, and solar radiation that affects crops. Average annual temperature ranges from 19.8 °C (67.6 °F) in the north (Tallahassee Airport) to 23.8 °C (74.8 °F) in the south (Homestead General Aviation Airport) (NOAA 2017b). Average annual rainfall ranges from 1,475 mm (58.1 in) in the north to 1,458 mm (59.5 in) in the south, with more rainfall occurring in summer than winter. Average relative humidity is 95% during the summer (Gainesville, mornings in September) and 47% in the winter (Orlando and Tallahassee, afternoons in April). Hurricanes can affect all of Florida but have been infrequent in recent years, with the only hurricanes making landfall in Florida being Wilma in 2005 and two in 2016 (NHC 2017). Parts of North Florida can also be affected by tornados. North and Central Florida are classified as humid subtropical, while South Florida includes savanna, monsoon, and rainforest (Peel et al. 2007).

Such a diverse and mild climate makes Florida suitable for growing many different crops including oranges, grapefruit, snap beans (fresh market), cucumbers (fresh market), bell peppers, squash, sweet corn, tomatoes (fresh market), watermelons, sugar cane, tangerines, and strawberries (Putnam 2015c) (Fig. 8.1). South Florida is warm enough for growing vegetables such as sweet corn, tomato, strawberry, green beans, and lettuce, even during winter. Florida's warm winters make it possible to grow tropical fruits and vegetables such as avocado, mango, cassava, boniato, and lychee in South Florida (Campbell 1994; Klassen et al. 2002). North Florida climate conditions are less favorable for this type of tropical fruit production, but are favorable for agronomic grain and fiber crops during the summer growing season (April to September). While some crops are regionally-specific in Florida, others are grown throughout the state but with varying production seasons and different market windows. Florida's agricultural land has been declining in recent decades, mostly due to economic drivers but sometimes due to disease pressure (e.g. citrus greening) and partly due to changes in climate (e.g., citrus). However, at the same time, Florida's agricultural production has grown steadily over the past four decades, due to increased efficiency and expanding irrigation.

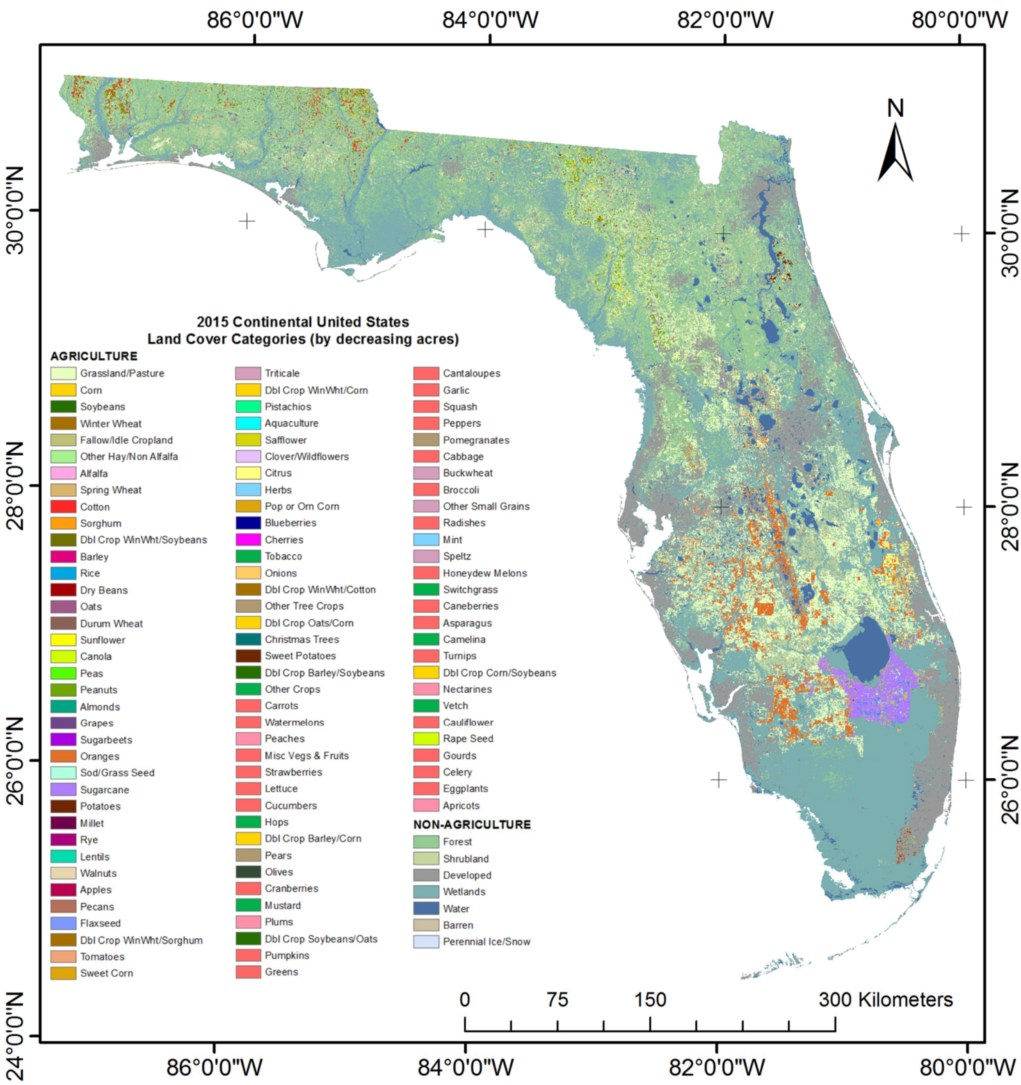

Figure 8.1. Distribution of crop areas in Florida (USDA-NASS 2016).

Crop growth and productivity, as well as the occurrence of pests and diseases, are all influenced by climate factors, including atmospheric CO_2 concentration, temperature, and rainfall. Crops can directly suffer damage from low temperatures (e.g., freezing), high temperatures (e.g., heat stress), strong winds (e.g., tornadoes and hurricanes), periods of low rainfall (e.g., droughts) or intensive rainfall events that can cause runoff, flooding, and/or erosion. Many pests and diseases flourish in high relative humidity conditions. Any change in climate factors will, therefore, affect crops directly or indirectly via pests and diseases (Walthall et al. 2013).

The frequency and intensity of extreme events such as heavy storms, flooding, hurricanes, and drought are expected to increase under projected climate change scenarios due to elevated temperatures and a resulting increase in the moisture-holding capacity of the air (National Academies of Sciences 2016; Anyamba et al. 2014). Agricultural productivity and water resources can be degraded with unfavorable sequences from these weather events, resulting in: substantial losses of soil, nutrients, and fertilizers in agricultural fields; pollutant loadings to waterbodies; and subsequent water quality issues, particularly in agriculturally dominated regions (Whitehead et al. 2009; Johnson et al. 2015). The National Climate Assessment (2014) concluded that climate change "is already affecting the American people in far-reaching ways" and that the future will be unlike the past. In Florida, some impacts of climate change on the state's agricultural economy have already been observed (Maul and Martin 1993; Scavia et al. 2002; Sallenger et al. 2012). For example, studies have found that the crop yields of vegetables such as snap beans, bell peppers, and tomatoes are related to El Niño Southern Oscillation (ENSO) phases. ENSO is an irregularly periodical variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, affecting much of the tropics and subtropics including Florida. Climate variability characterized by freeze probabilities have also directly affected Florida's citrus production (Hansen et al. 1999; Miller and Glantz 1988). And the fact is that climate change and variability will continue to affect Florida's agricultural productivity in the coming decades through increased or more intense occurrences of extreme events, such as droughts, floods, and storms (Adams et al. 1990; Hansen et al. 1998; Reilly et al. 2003; Gao et al. 2012).

The United States Department of Agriculture (USDA) defines food insecurity as "limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways" (Anderson 1990). And the USDA's National Food Security Surveys are the main tools to measure food security. The most recent survey in 2015 found that 12.7% (one million) of the eight million Florida households were food insecure, and 5.4% (447,000) of the households had very low food security. Climate change will likely make it more difficult to improve those statistics, thus the poor will suffer more from climate change (Lobell et al. 2008; Mendelsohn et al. 2006). Understanding agricultural implications of climate change is critical in developing the climate change adaptation strategies and methods needed to achieve improved food security and agricultural sustainability in Florida.

In the coming decades, Florida farmers will need to take steps to adapt to climate change; that is, they must choose to make investments today to offset climate changes' negative impacts and take advantage of possible positive impacts in the future. The economic challenge will be for farmers to be able to increase productivity and incomes while they cope with temperature and precipitation patterns that are increasingly likely to be unfavorable. This chapter gives an overview of Florida's agriculture and describes expected agricultural impacts of climate change. In addition, agricultural adaptation strategies to climate change in Florida are discussed, and recommendations are made for future research needs.

Florida's Agriculture

Florida's agriculture is among the most diverse in the U.S., contributing over 300 commodities to national and international markets (Putnam 2011; Putnam 2015c). Land dedicated to agriculture in Florida has slowly decreased from 4.2 million ha (10.3 million acres) in 2002 to 3.8 million ha (9.4 million acres) in 2015 (USDA-NASS 2017; Putnam 2015b; Fig. 8.2). The market value of Florida's agricultural products from the state's 47,600 commercial farms was estimated to be $8.5 billion US dollars in 2013 (Putnam 2015c; Figs. 8.3 and 8.4), and that market value has grown steadily over the past four decades (Fig. 8.3).

Florida agriculture encompasses a variety of commodity groups including grains, fiber, vegetables, fruits, nursery and floriculture, livestock, and aquaculture. Of these, the crops producing the greatest sales are oranges, sugarcane, foliage plants, strawberries, tomatoes, and peppers (Fig. 8.5). In the 2013-2014 season, Florida accounted for 59% of the total U.S. citrus production with 105 million boxes of citrus (Putnam 2015c). And Florida ranked second in the nation in the production of greenhouse and nursery products as well as vegetables including melons and potatoes, with cash receipts totaling over $7.7 billion (USDA-NASS 2017). Livestock also contributes to Florida's commodity receipts, with cattle and calves, milk, poultry, and eggs being the most prominent.

Florida crops are often irrigated due to frequent periods of low rainfall in the state, particularly in winter. In 2012, approximately 11,744 farms (25%) had irrigated crops (USDA-NASS 2012). The total irrigated area in Florida is estimated to be 1.65 million ha (4.08 million acres), which is 21% of the total agricultural areas in Florida, using an average 3.5 million liters per hectare (350 mm or 0.37 million gallons per acre) annually (FDACS 2016; USDA-NASS 2012). A variety of methods are used for irrigation including center pivot, drip, gravity systems, sprinkler, spray, overhead, and traveling irrigation guns. In Florida, water is also applied to prevent crops from freezing (frost damage). Citrus and sugarcane production is estimated to apply 5 billion liters (1.3 billion gallons) of water per day on average, with some of this for freeze-protection; this is 61% of the total irrigation water (8 billion liters per day or 2.1 billion gallon per day) applied in Florida (FDACS 2016). And agricultural water use is expected to increase 17% by 2035 (FDACS 2016).

Each year, Florida dairies produce more than 1.1 billion kilograms (2.5 billion pounds) of milk valued at $560 million, from 122,000 cows (Putnam 2015c; USDA-NASS 2017) (Fig. 8.6). There are 1.7 million head of beef cattle (0.9 million beef cows and 0.8 million calves) on Florida farms and ranches, primarily located in southwest Florida (Okeechobee, Osceola, and Polk counties). The cash receipts from cattle and calf marketing are about $838 million. Nationally, Florida ranked 10th in beef cows and 19th in milk cows. Hens and pullets of laying age on farms amount to about nine million birds that produce 2.4 billion eggs corresponding at a market value of $219 million every year. Florida also produces about 63 million broilers each year, valued at

$170 million. Florida has about 18,000 hogs valued at $3.1 million, and 54,000 goats for milk and meat in Florida.

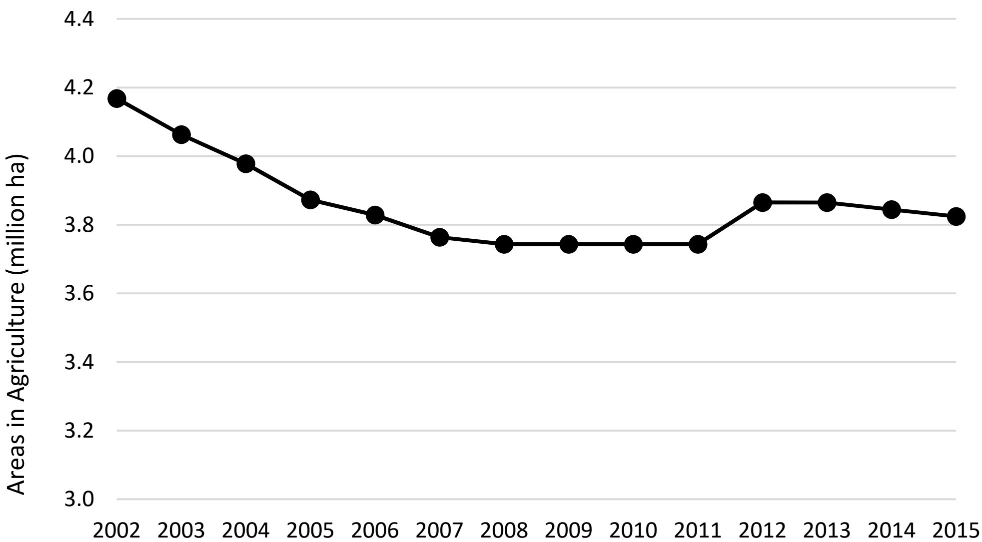

Figure 8.2. Agricultural areas in Florida (Putnam 2015b).

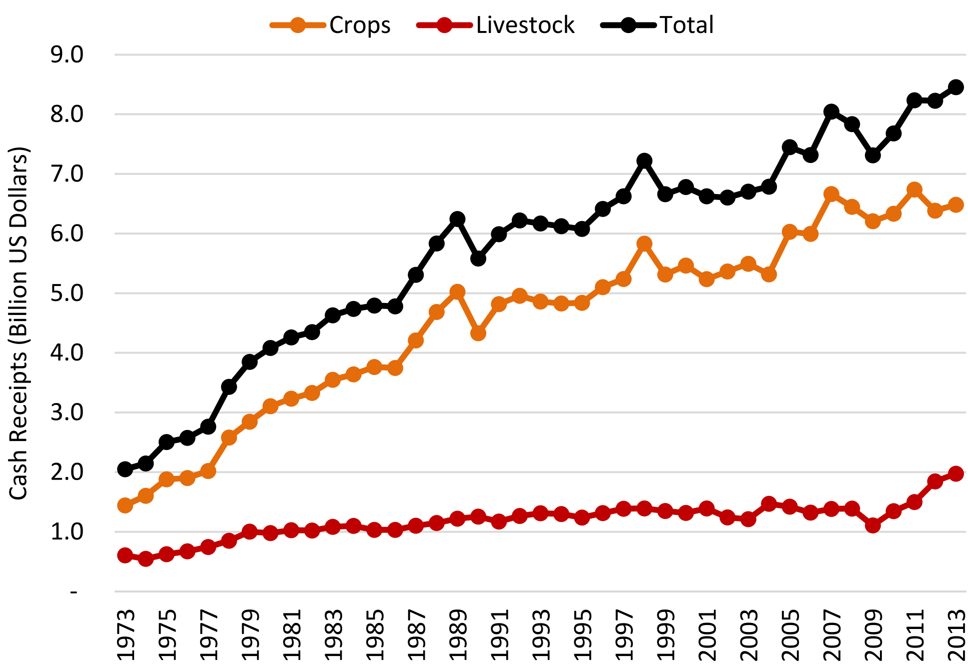

Figure 8.3. Florida's agricultural production in cash receipts (Putnam 2015c).

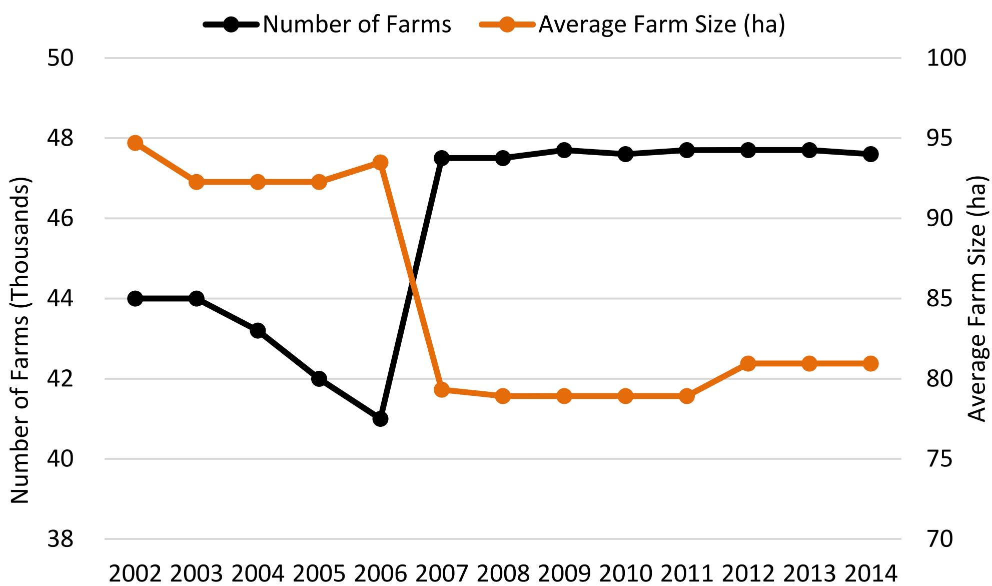

Figure 8.4. Number and average size of farms in Florida (Putnam 2015c).

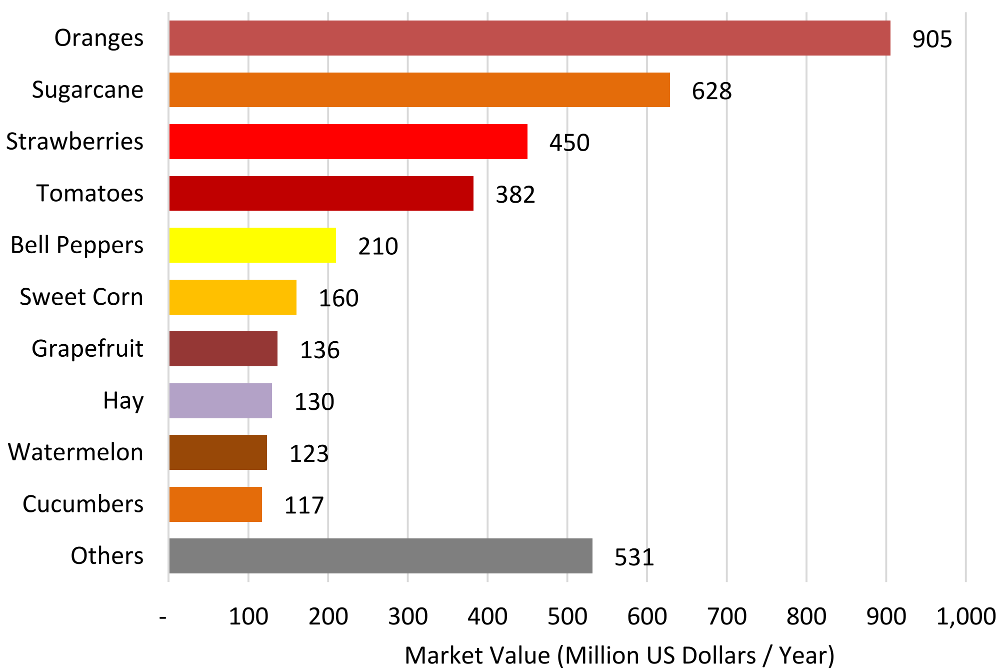

Figure 8.5. Market values of Florida crops (USDA-NASS 2017).

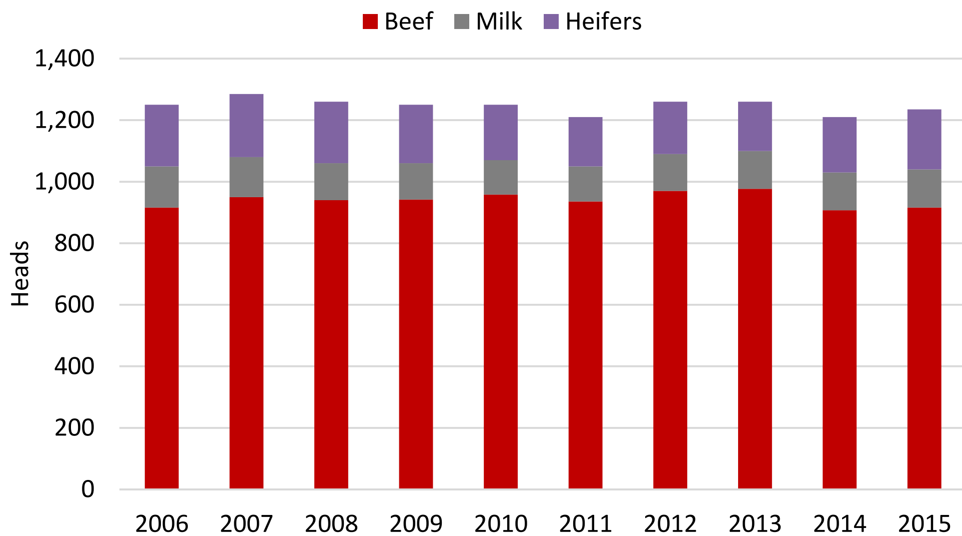

Figure 8.6. Head of beef and dairy cows in Florida (Putnam 2015c).

Climate Change Impacts on Florida's Crop Production

Elevated Atmospheric CO_2

Since accurate CO_2 recording was initiated in 1958 at Mauna Loa, Hawaii, the atmospheric CO_2 concentration has increased from 316 to 404 ppm in 2016, a 28% increase (NOAA 2017a). Projected atmospheric CO_2 concentration will reach more than 500 ppm in this century (Pachauri et al. 2014). An analysis with CO_2-dependent photosynthesis equations in the Decision Support System for Agrotechnology Transfer (DSSAT) crop models (Jones et al. 2003) indicates that yields of crops such as peanuts would have increased by 17% due to the CO_2 increase over that same period. The degree of crop yield increase from elevated CO_2 depends on the photosynthetic features of a crop, which are commonly characterized by C_3 and C_4 pathways. C_3 crops have CO_2 responsive photosynthesis (often called temperate or cool season plants) and include beans, rice, and potatoes. On the other hand, the C_4 crops are less responsive to elevated atmospheric CO_2 concentrations but have higher temperature optimums for photosynthesis (corn and sugarcane) and are called tropical or warm season plants.

In the 1980s when research on crop CO_2 response had just begun, the so-called ambient reference point was about 330 ppm. In later years 350 ppm CO_2 was used as the reference point. Assuming a starting point of 350 ppm CO_2, early research showed that C_3 photosynthesis crop yields (temperate dicots and cereals such as soybean, peanut, dry bean, rice, and wheat) increased about 30% with a doubling of CO_2, from 350 to 700 ppm for rice (Baker et al. 1990; Baker et al. 1992; Baker et al. 1995), peanuts (Prasad et al. 2003), common beans (Prasad et al. 2002), cotton

(Reddy et al. 2000), and tomatoes (Tripp et al. 1991). Except for sweet corn (which is a C_4 plant), all of Florida's vegetable crops, fruits, and citrus are C_3 species and are presumed to have CO_2 responses similar to the other C_3 crops (for details see summaries of measured crop response to CO_2 reviewed by Backlund et al. (2009) and Kimball et al. (2002), and crop model responses to CO_2 reviewed by Boote et al. (2010)). The response of C_3 crops to rising CO_2 is asymptotic, tending toward saturation at about 700 ppm. Thus, the yield improvement above present 400 ppm CO_2 will be occurring at a lesser rate, and the beneficial effects of this aspect of climate change are declining (i.e. saturating). On the other hand, the response to CO_2 is much less for those crops with a C_4 photosynthetic pathway, such as corn, sugarcane, sorghum, millet, and nearly all of Florida's tropical grasses (Ghannoum et al. 2000; Leakey et al. 2006; Manderscheid et al. 2014; Rosenzweig and Hillel 1998; Tubiello et al. 2002).

At the present-day levels of atmospheric CO_2 of 400 ppm, there are recent reports of no response to CO_2 for maize (Ghannoum et al. 2000; Leakey et al. 2006; Manderscheid et al. 2014). In CO_2-Free Air Carbon Dioxide Enhancement (FACE) experiments in Illinois (in which an elevated CO_2 concentration is maintained under field conditions by constantly blowing air with elevated CO_2 concentration into a field experiment to create future CO_2 conditions), maize yields were not increased by elevated atmospheric CO_2 under well-watered conditions (Leakey et al. 2006; Twine et al. 2013). The CO_2-FACE experiments in Germany (Manderscheid et al. 2014) likewise showed a non-existent yield response to elevated atmospheric CO_2 increase from 387 to 550 ppm for irrigated maize, although yields were responsive to CO_2 under water-deficit conditions. Prior to those FACE studies, there was only one experiment on maize grown to maturity (King and Greer 1986) that reported a 6.2% and 2.6% increase with atmospheric CO_2 concentration elevated from 355 to 625 ppm and 875 ppm, respectively (this translates to less than a 2% response for the smaller increment from 376 to 542 ppm CO_2 in the Illinois FACE experiments). There are few studies of yield response to CO_2 for other tropical C_4 species, and sorghum among them was responsive only under water-deficit conditions (Ottman et al. 2001). Bahiagrass (*Paspalum notatum* Flüggé), the most common pasture grass in Florida, presented a 9% response to CO_2 increasing from 360 to 700 ppm (Fritschi et al. 1999; Newman et al. 2001; Newman et al. 2006). Simulated biomass response for corn, sugarcane, and tropical grass (the C_4 species) in the Decision Support System for Agrotechnology Transfer (DSSAT) crop models (Jones et al. 2003) is 4.2% with a doubling of CO_2, going from 350 to 700 ppm, with simulated increases between 1–2% (statistically not detectable in field studies) for a CO_2 increase from 387 to 550 ppm. The response of crops to elevated atmospheric CO_2 concentrations is greater under drought stress and water limitation (Kimball et al. 1995; Sionit et al. 1981), especially for C_4 crops such as sorghum (Ottman et al. 2001) and maize (Manderscheid et al. 2014). However, the response to CO_2 is much less under nutrient, particularly nitrogen, limitations (Sionit et al. 1981; Kimball et al. 1995).

Rising CO_2 is expected to have modest effects to reduce crop transpiration (and hence evapotranspiration), but the exact effect is confounded by the extent to which elevated atmospheric CO_2 concentration increases crop leaf area index (which increases transpiration) as well as compensations in crop energy balance processes by which any decrease in transpiration results in an increased canopy temperature. Leaf conductance is reduced on average by about 38–40% with a doubling of CO_2 from 350 to 700 ppm (Morison 1987); however, whole crop transpiration is only reduced by about 9–10% under the same doubling of atmospheric CO_2 (Backlund et al. 2009). Concurrently, midday foliage temperature increases about 1–1.5 °C (1.8–2.7 °F) with doubling of CO_2 (Prasad et al. 2006) due to stomatal closure and less transpiration causing a warming of the canopy as a way to dissipate energy; but warming, in turn, increases transpiration and possibly enhances the impact of high temperature on crops. Sometimes there is no reduction in transpiration when the elevated atmospheric CO_2 concentration stimulates additional leaf area growth (Allen et al. 2003). The C_3 and C_4 crops differ in their degree of transpiration reduction, with C_3 crops near 8–10% reduction with doubled CO_2 (350 to 700 ppm) (Allen et al. 2003; Bernacchi et al. 2007; Backlund et al. 2009), while C_4 crops such as maize and sorghum show about 18% reduction (Allen et al. 2011; Chun et al. 2011).

Elevated CO_2 concentration has been shown to inhibit protein assimilation in main food crops (Bloom et al. 2010), but less is known about this effect in vegetables and fruits. Similarly, elevated CO_2 concentrations have been shown to reduce zinc (Zn) and iron (Fe) concentrations in major grains (Myers et al. 2014), but less is known how this might affect other crops grown in Florida.

Table 8.1. Climate change impacts on crops.

Changes	Positive Impacts	Negative Impacts
Elevated CO_2 concentration	Increased growth rate Increased water use efficiency	Increased weeds Decreased nutritive products Warmer canopies
Increased temperature	Less frost damage Improved winter growth Earlier planting	Faster phenology Reduced chill hours Increased heat stress Increased water use Increased pest/disease Increased risk of freeze if early flowering Crop water-logging/flooding Decreased arable lands (due to salt water intrusion induced by sea level rise)
Intensified rainfall and prolonged dry period		Increased runoff Increased erosion Increased irrigation requirement Increased chemical leaching

Rising Air Temperature

Many crops in Florida are grown at air temperatures that typically already exceed the optimum for a crop. This applies to maize and soybean, for which optimum temperature conditions are 23–24 °C (73–75 °F), matching temperatures presently experienced in the Midwestern United States, but are often higher in Florida. Some wheat and barley are grown in northern Florida over winter, but temperatures then are already too warm and chill requirements are often not adequately met in some years (compare this to the cool temperatures in northern Europe where wheat yields are often the highest, or to the Midwestern United States, which is generally cooler than Florida). Crops such as snap beans and tomatoes are grown only in winter–spring in Florida, but not in the summer because temperatures are too high and prevent bean and fruit formation. The optimal temperatures for the growth of citrus, tomatoes, and sugarcane are 20–30 °C (68–86 °F), 19–25 °C (66–77 °F), and 26–27 °C (79–81 °F), respectively (Morton 1987; Sato et al. 2000; Ebrahim et al. 1998). Temperatures outside the optimal ranges will decrease crop growth. Thus, increased temperatures may lead to the northward shift of some crops (EPA 1997).

Rising temperatures shorten crop life cycles, thus reducing resource capture and often resulting in a reduced yields (some of this might be overcome by crop breeding to recover the crop cycle). Another response could be slightly reduced daily photosynthesis depending on the crop. Crop respiration increases with rising temperatures but is often not the main reason for large yield reductions. As temperature increases further, fruit set and grain set are reduced, first slowly but eventually reaching a cut-off where zero pollen fertility occurs (this happens to tomatoes and snap beans during the summer in Florida). Crops differ in their failure point temperatures as described in the next paragraph.

The response of a number of Florida crops to increased temperatures has been evaluated in sunlit, controlled-environment chambers by University of Florida researchers. Findings for rice, beans, peanuts, soybeans, and sorghum are summarized here.

The optimum temperature for rice yield is 25 °C (77 °F) mean daily temperature (compare to a T_{max}/T_{min} of 30/20 °C (86/68 °F)) (Baker et al. 1992; Baker et al. 1995). Summer temperatures in Florida are 2–3 °C (3.6–5.4 °F) warmer than that optimum, and yield declines slowly, at first above 25 °C (77 °F) but reaching complete failure at 35 °C (95 °F) (compare to a T_{max}/T_{min} of 40/30 °C (104/86 °F)). The optimum temperature for bean yield is below 23 °C (73 °F), the coolest optimum temperature in that study, and seed-set and seed yield of beans failed completely at 32 °C (90 °F) mean temperature (Prasad et al. 2002).

The peanut, an important Florida crop, was grown from sowing to maturity at a range of temperatures in the same chamber system. The optimum temperature for peanut pod yield was less than 26 °C (79 °F), the coolest treatment of that study (Prasad et al. 2003). By contrast, present average temperatures in Florida's peanut growing season are about 27 °C (81 °F). These studies showed that peanut yield is expected to decline progressively as temperature increases until a failure of yield is projected at about 40 °C (104 °F) mean temperature. Soybeans have a similar yield response to temperatures, and the total failure of seed yield also occurs at about 39 °C to 40 °C (86 to 104 °F) mean temperature (Allen and Boote 2000; Boote et al. 2005; Pan 1996).

Sorghum, while not an important crop in Florida, has a sensitivity to temperature (Prasad et al. 2006) that is very similar to rice (also not an important crop in Florida), with an optimum at or below 25 °C (77 °F) (note: the 32/22 °C (90/72 °F) diurnal temperature cycle was the lowest temperature tested). Sorghum, like rice, had complete failure at 35 °C (95 °F) (40/30 °C (104/86 °F) diurnal cycle). By analogy to these two warm-season cereals, rice and sorghum, we assume that maize has a similar temperature sensitivity.

A common key feature in all of these experiments (rice, beans, peanuts, soybeans, and sorghum) is that the upper failure temperature threshold is associated with progressive failure of pollen viability and seed-set, and subsequently reduced seed harvest index and yield (Boote et al. 2005; Prasad et al. 2002; Prasad et al. 2006; Prasad et al. 2003; Baker et al. 1995). Soybeans and peanuts are the most tolerant, maize-sorghum-rice have moderate tolerance, while bean and tomato crops are very susceptible to rising temperature (see percent seed-set of these crops in Fig. 8.7). Indeed, present high summer temperatures are the cause for tomato and green bean crop failure to produce any tomatoes or beans because of non-viable pollen when planted late (May onward), thus exposing plants to high temperatures during fruiting. Hot conditions of maximum day temperatures above 32 °C (90 °F) and/or minimum night temperatures above 21 °C (70 °F) cause increased pollen sterility and reduced fruit set in tomatoes (Benedictos and Yavari 1997; Sato et al. 2000). There will certainly be increased pressure on tomato and bean breeders to obtain genetic heat tolerance (e.g. via breeding programs) or for growers to sow crops earlier (provided there is no freeze risk).

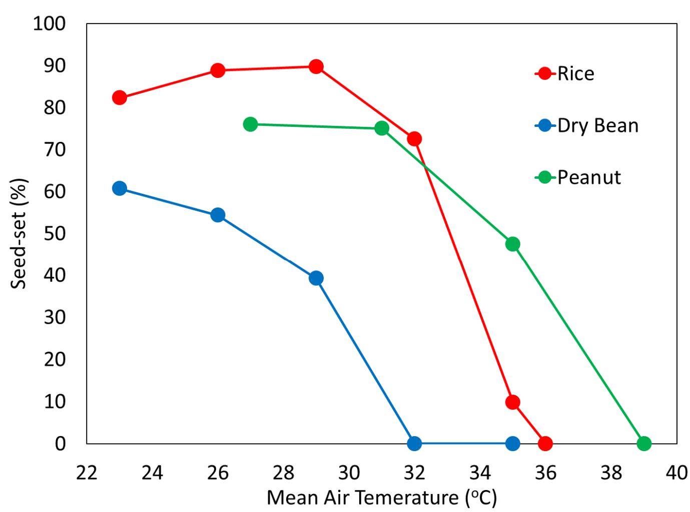

Figure 8.7. Percent seed set of rice, dry beans, and peanuts in response to temperature (Baker et al. 1995; Prasad et al. 2002; Prasad et al. 2003). Seed set is very closely related to yield, and a lower seed set means a lower yield.

Forage crop response to temperature varies and temperature effects are different from the effect on grain crops. The C_3 grasses, such as ryegrass or wheat used for grazing, are responsive to rising temperatures; small increases in temperature during winter season may actually stimulate growth, although also triggering earlier onset of flowering and thus less total forage production. The vegetative growth of C_4 tropical grasses (for which seed-set is not an issue) responds positively to rising temperatures at all times of the year, and experiments on bahiagrass showed increased production with up to 4 °C (7.2 °F) higher temperature, provided water is not limited (Fritschi et al. 1999; Newman et al. 2001; Newman et al. 2006). By analogy, but with no experimental evidence, the same response could potentially be expected for sugarcane, although sugar concentration in stalks is likely to be lower.

Changing Rainfall Pattern and Irrigation Demand

Rainfall is an important climate factor that influences plant growth and may also be supplemented by producers (via irrigation). Agricultural production has long been dependent on rainfall and irrigation for optimum yields. Because of alternating wet and dry seasons, the range of commodities grown in Florida will benefit from supplementary irrigation. Irrigation provides an input for Florida agriculture to grow a variety of crops and target market windows that allow the various commodities to be economically viable. Climate change and climate variability introduce uncertainty into the availability and quality of water for irrigation and the potential for Florida producers to meet the desired market windows.

Current user demands on freshwater supplies are already causing disputes, as is illustrated by the Florida/Georgia conflict in the Apalachicola-Chattahoochee-Flint River Basin (Stephenson 2000). In 2013, Florida sued Georgia in the US Supreme Court over water use in this basin and identified reduced water flow into Florida as a result of increased agricultural irrigation water withdrawals in Georgia. The Tampa Bay conflict is another example of the competing demand of water resources (Regan 2003). Thus, the potential change in freshwater quantities that may result from climate change will contribute additional stress to the water supply system. Climate changes that might influence available freshwater, and thus irrigation, are directly connected to the timing and amount of rainfall received and the rate of evapotranspiration or water losses from the system.

Climate change impacts on the frequency and amount of rainfall have a direct influence on available water for irrigation as well as the amount of irrigation needed to produce an agricultural crop. Climate change predictions for rainfall have shown an increase in extreme rainfall intensity, with greater increases near the coast and lower increases inland for Florida locations (Wang et al. 2013). Rainfall that occurs with greater intensity will result in less total effective rainfall for use by crops because of the low water holding capacity of Florida soils. This, in turn, will lead to greater irrigation needs to maintain crops under current farming practices. Furthermore, agricultural water demand increases due to a warmer and drier climate will compete with other water resource uses (EPA 1997). Model projections have suggested that total rainfall amounts will be reduced with climate change in Florida (Biasutti et al. 2012; Todd et al. 2012). Lower rainfall totals will translate into less recharge to water supplies and therefore less available water for irrigation. In addition, lower rainfall will result in greater irrigation needs depending on the distribution of rainfall events. Some caution is warranted with these potential future scenarios of rainfall change as rainfall projections are uncertain. Further research is needed to better understand how Florida rainfall will change in the future (Misra et al. 2011).

While changes in rainfall have a direct impact on irrigation, changes in evapotranspiration also influence irrigation needs. Climate change models have projected increases in annual atmospheric evapotranspiration demand of 70 to 130 mm (2.76 to 5.12 inches) by 2050 in Florida (Obeysekera 2011). The projected higher atmospheric evapotranspiration demand for future climate scenarios would translate into greater crop water needs for irrigation under current farming conditions. However, the effects of elevated atmospheric CO_2 concentration on stomatal conductance and transpiration may compensate/offset temperature-induced increases in evapotranspiration (Backlund et al. 2008). The potential changes related to evapotranspiration, such as temperature and solar radiation, could have other effects on agricultural production and thus irrigation. For example, temperature changes will influence the timing and rate of crop development. The shifting of a crop season and harvest would create additional irrigation modifications, which could be either an increase or a decrease depending on the timing.

Another climate change concern for agricultural irrigators is the quality of water used for irrigation. Sea level rise will increase the risk of salt water intrusion into aquifers that are used for irrigation purposes (Karl 2009). Thus, some groundwater wells used for irrigation may no longer be viable as freshwater supplies. Alternative water sources or water treatment will be needed for agriculture in areas where salinity concentration exceeds the level that is safe for crops.

Irrigation strategies that could be explored as an adaptation to climate change in Florida agricultural production include primed acclimation, deficit irrigation, drought-resistant crops, and variety (cultivar) improvements. Primed acclimation refers to the practice of providing deficit irrigation amounts during the initial phases of crop development and full irrigation amounts in the later portion of crop development to create a more resilient plant (Rowland et al. 2012). Deficit irrigation refers to providing a less than optimum irrigation for the entire production period of a crop. Thus, primed acclimation is a variation of a deficient irrigation strategy where deficit amounts are applied in the early season of crop development. Reducing overall irrigation inputs is one strategy for addressing the projected change in agricultural systems due to climate change. Another strategy is to grow crops that are more efficient water users either through improved breeding or alternative crops. Irrigated agriculture will likely need a combination of strategies to remain viable under predicted climate change conditions. The future viability of irrigated agriculture in Florida will depend on the ability of producers to successfully implement new strategies that adapt to climate change.

Salt Water Intrusion from Sea Level Rise Affects Crops and Irrigation Needs

Increased air temperature will accelerate melting of ice sheets and glaciers on land, which will increase the volume of water in the oceans and then the sea level (Nicholls and Cazenave 2010). As warmer water takes up more volume (thermal expansion), the sea level will also be raised as seawater is warmed by increased air temperature (Nicholls and Cazenave 2010). The sea level rise will not be uniform spatially, but will be more prominent along the equator due to the centrifugal force of the Earth's rotation; thus, the amount of sea level rise will be higher in Florida than other coastal states. Raised sea level will further the intrusion of salt water into coastal aquifers, which will increase the salinity of groundwater and then soils (Prinos 2016; Ketabchi et al. 2016). In South Florida, for instance, sea level has been rising by 2.32 mm/year (0.0913 in/year, Daytona Beach, 1925–1983) to 2.78 mm/year (0.1094 in/year, Vaca Key, 1971–2006) in the past (Zervas 2009). If sea level rises by 1.0 m (3.28 ft) by 2060, which is close to the National Oceanic and Atmospheric Administration's (NOAA) "High" scenario (1.03-m increase) (Sweet et al. 2017), then about 2,000 km2 (770 mi2) of three counties—Miami-Dade, Broward, and Palm Beach— in South Florida will be below the projected sea level (Zhang 2011) resulting in loss of Florida's agricultural land in that region.

The Floridan aquifer system is an important source of freshwater in Florida and it is shallow and highly permeable, which makes the aquifers more vulnerable to sea level rise and saltwater intrusion. The aquifer systems have been experiencing saltwater intrusion caused by sea level rise, leading to the contamination of wells for agricultural and domestic water supplies and changes in water management practices, especially in South Florida (Blanco et al. 2013; Trimble et al. 1998; Heimlich and Bloetscher 2011). Increased salinity in groundwater will result in increased irrigation costs and then cropping system will decrease in productivity and profitability. Salty irrigation water will lead to an accumulation of salts in soils and increase soil salinity, which will require more freshwater irrigation to wash it out or, in some cases, it will result in soil degradation and loss of arable land.

Climate Change Impacts on Florida's Livestock Production

The increase in air temperatures associated with climate change will affect livestock production directly and indirectly (Thornton 2010; Reynolds et al. 2010). Rising temperature can increase heat stresses, illness, diseases, and mortality, which subsequently reduce the productivity of livestock (Nardone et al. 2010; Rojas-Downing et al. 2017; Das et al. 2016). Increased temperatures will promote the growth of some forage crops but decrease nutrient availability (Rojas-Downing et al. 2017; IPCC 2007). In addition, the feed intake and digestive efficiency of livestock decreases at high temperatures (Mader and Davis 2004; Tankson et al. 2001). Dairy cows produce less milk, and meat production can decrease due to reduced growth rate at increased temperatures (Nardone et al. 2010; Mitlöhner et al. 2001). In addition, reproduction of cows, pigs, and poultry decreases with increases in temperature (Hansen 2007; Nardone et al. 2010; De Rensis and Scaramuzzi 2003; Kunavongkrit et al. 2005). Prolonged exposure to high temperatures can affect livestock health, metabolism, and liver function (Bernabucci et al. 2006). When livestock performance is high, livestock production will be more vulnerable to high temperatures (Hahn 1999). Such adverse impacts of climate change could lead to the northward movement of livestock production in Florida and into other parts of the USA (EPA 1997; Von Lehe 2007).

Table 8.2. Climate change impacts on livestock and their feed sources.

Changes	**Positive Impacts**	**Negative Impacts**
Increased temperature	Increased herbage growth	Decreased nutrient quality of feed Decreased feed intake Decreased efficiency of feed conversion Decreased milk production Decreased meat production Decreased reproduction Increased mortality Increased diseases
Intensified rainfall and prolonged dry period		Decreased forage growth and quality Decreased pasture biodiversity Increased flood damage Decreased forage quality Changed optimal growth rate
Elevated CO_2 concentration	Increased herbage growth Reduced transpiration Improved water use efficiency	Decreased nutrient quality of forage/feed

Increased frequency of extreme events such as drought and flood can degrade the quality of forage. Dry periods prolonged by increased air temperatures will affect the growth of forages and feed crops and will reduce their nutrient availability for livestock (Polley et al. 2013). In addition, rising temperatures will increase evapotranspiration and decrease soil water content. Warmer air can hold more moisture, which can result in more intense storm events. Increased heavy storm and flood frequency is another impact we can expect with climate change (Schmidt 2000). Such hydrologic consequences of climate change will lead to a reduction in forage and feed crop production, and subsequently increase feed costs and decrease cattle and poultry products such as milk, meat, and eggs. Combined changes in temperature and rainfall can promote the spread of vector-borne pests such as flies, ticks, and mosquitoes, as well as increase livestock diseases (Thornton et al. 2009; Rojas-Downing et al. 2017; Kurukulasuriya and Rosenthal 2003). For instance, the hydrologic condition (surface wetness and groundwater table depth) of the land surface was found to be associated with the transmission of the West Nile Virus to chickens in South Florida (Shaman et al. 2005; Day and Shaman 2008).

Adaptation Strategies

Overall

Adaptation to expected changes in climate is of considerable importance to the long-term sustainability of agricultural production in Florida. Adapting to climate change can be achieved through a broad range of management alternatives and technological advances. While decision-making in agriculture involves many aspects beyond climate, including economics, social factors, and policy considerations, climate-related risks are a primary source of yield and income variability. Researchers and cooperative extension services must play a proactive role to cogenerate necessary responses and technologies that farmers will need to handle such future challenges. In addition to improving and/or developing management practices and technologies, climate literacy of extension faculty and producers is required, as well as climate information and decision support systems to help the industry mitigate risks associated with climate variability and change.

A wide range of management practices can help producers adapt and increase the resilience of agricultural production systems to climate variability and change. Many aspects related to vulnerability (defined as the degree of sensitivity) and ability to cope with climate variability, and adaptation (defined as adjustments to environmental stresses caused by climate variability) can also be applied to climate change (Fraisse et al. 2009). Existing strategies, mostly developed for row crops—such as the use of high-biomass winter cover crops, conservation tillage, sod-based rotation systems, efficient irrigation technologies, and precision agriculture—can help producers minimize the risks associated with climate variability and change as well as improve their resource-use efficiency.

High Residue Cover Crops

High-residue cover cropping is an adaptation of conservation tillage in which a high-biomass cover crop is grown during the winter and is rolled or cut down prior to no-till or strip-till planting in the spring. Examples of winter cereals used as high residue cover crops include rye (*Secale cereale*), black oats (*Avena strigosa*), wheat (*Triticum*), or triticale (*Triticosecale*). High-residue cover crops and reduced tillage can lessen some negative impacts from climate and weather, such as high-intensity rainfall events, spring and summer dry spells, droughts, and extreme soil temperatures during critical crop reproduction periods. Keeping soil covered year-round with crop residue can reduce soil erosion, improve water infiltration, reduce evaporative moisture loss, and moderate soil temperature. Some benefits depend on the climate and soil types of the system, and these positive impacts can increase with repeated use of high-residue cover crops. The main differences between high-residue cover crops and traditional winter cover crops are the types of crops selected and the amount of fertilizer applied. A high-residue system uses winter cereals with fertilizer applications, resulting in greater production of biomass than a traditional cover crop system. Many producers find the cost of high-residue cover crops are justified in dryland systems because of the improved water management and soil quality that result from greater crop residues (Joel Love 2015).

Conservation Tillage

The U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) defines conservation tillage as a system that leaves enough crop residues from cover crops and/or cash crops on the soil surface after planting to provide at least 30% soil cover. Research has identified 30% soil cover as the minimal amount of residue needed to avoid significant soil loss, but greater residue amounts are preferred. The use of cover crops is critical to producing this additional plant residue. In addition to maximizing surface residues, conservation tillage can increase below-ground disruption to eliminate compacted soil layers by maintaining plant roots and soil macropores. While conservation tillage can resolve the occurrence of a shallow plow-compacted layer in some systems, subsoil tillage may be required in some soils to manage compaction from vehicle traffic or from naturally occurring compacted layers. Together with cover crops, conservation tillage has the potential to reduce erosion, increase rainfall infiltration, reduce subsurface compaction, and maximize soil organic carbon accumulation, which positively affects many soil physical and chemical properties. The main way that conservation tillage can reduce risks related to climate variability (particularly droughts and dry spells) is by increasing the water available to plants. Areas where conservation tillage is used have revealed a number of benefits including reduced erosion and runoff, increased water infiltration, more plant-available water, reduced soil water evaporation, and reduced diurnal soil temperature fluctuations (Balkcom et al. 2012).

Sod-Based Rotation

A sod-based rotation incorporates two or more consecutive seasons of a perennial grass into a conventional row-crop rotation. One example of a sod-based rotation is an adaptation of the conventional peanut/cotton rotation that farmers follow in North Florida. In a four-year, sod-based rotation, bahiagrass is grown for two years, followed by a year of peanuts, and then a year of cotton (Fig. 8.8). Such rotation is beneficial to the many soils in Florida that have a high sand content, low organic matter, and compaction layers making them more vulnerable to stresses from variability in climate, namely dry spells and droughts (Wright et al. 2015).

Sod-based rotation can reduce climate-related risks by increasing soil water holding capacity, potentially reducing the negative effects of droughts and dry spells, increasing the water infiltration rate, and reducing soil bulk density. The soil water holding capacity is increased as a result of improved soil organic matter promoted by the sod-based rotation. Increased infiltration rate and reduced soil bulk density results from an increase in soil macropores due to greater root mass and biological activity for soils. Field data from 2002 to 2007 in Quincy, Florida showed that water-use efficiency of peanut crops under sod-based rotation was 15% greater in irrigated fields and 19% greater in dryland fields compared to the water-use efficiency of peanut crops in a conventional rotation (Zhao et al. 2008). Here, water-use efficiency is defined as the ratio of crop yield to the sum of irrigation and rainfall. These data suggest that yield increases have resulted from improvements in soil water-holding capacity. In the very dry years of 2006 and 2007, peanut yields in a sod-based rotation were 13% greater than those under conventional rotation (Zhao et al. 2008).

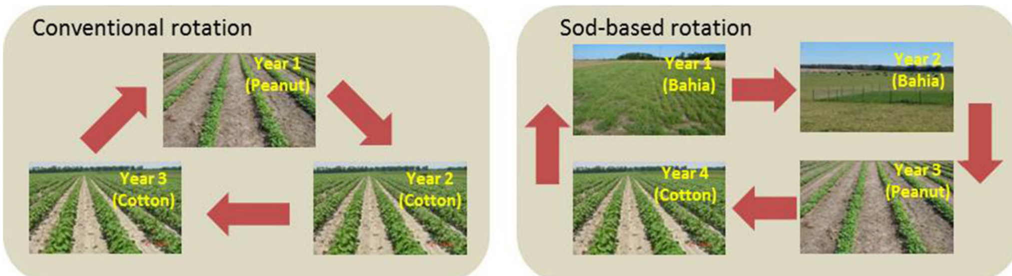

Figure 8.8. Illustration of conventional and sod-based peanut/cotton rotations. Credits: David Wright (Wright et al. 2015).

Irrigation

The International Panel on Climate Change (IPCC) indicated in their most recent report (Field et al. 2014) that there is medium confidence that drought will intensify in the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration. With that in mind, irrigation, if available, can be considered as a potential alternative for reducing the risk of yield losses especially in soils with low water-holding capacity, such as those common in Florida. While irrigation requires considerable investment over dryland production, it can also result in considerable increases in yields and profits. However, irrigation management must be as efficient as possible to avoid losses and groundwater contamination.

Center pivot, micro, and subsurface drip irrigation systems require different investment costs and management practices. Micro-irrigation is the slow, frequent application of water directly to relatively small areas adjacent to individual plants through emitters placed along a water delivery line. Water is generally conveyed in low-pressure, flexible plastic tubing. Water must be of high quality to avoid clogging the small emitters; this is often managed with filtration and occasional chemical treatments. A principal advantage of micro-irrigation is that non-beneficial evaporation—meaning evaporation of water from soil surfaces that do not contribute to crop growth—is greatly reduced when compared to sprinkler irrigation (Zotarelli 2015). Subsurface drip irrigation water is applied below the soil surface through driplines that are installed at a depth of 30–46 cm (12–18 in). Tillage, planting, and other field operations are not impeded by driplines because they are established at a sufficient depth to allow for those operations and long-term use. Emitter flow rates for subsurface irrigation are generally less than 11.4 liters/hour (3 gallons/hour). Subsurface drip irrigation can have a useable lifetime of up to 20 years, making it economically competitive with center pivot irrigation used for low-value commodity row crops (Lamm et al. 2010).

Center pivot irrigation consists of a galvanized steel lateral that rotates in a circle around a fixed point (pivot) in the center of a field. The lateral is supported above the crop on A-shaped steel frames using cables and trusses. Sprinklers are used to distribute the water across the field, as the area to be irrigated increases towards the outer end of the lateral, thus varied size or spacing of sprinklers is used to gradually increase the water application rate. Variable-rate irrigation is an innovative technology that enables a center pivot irrigation system to optimize irrigation application. Most fields are not uniform because of natural variations in soil type or topography. When water is applied uniformly to a field, some areas of the field may be overwatered while other areas may remain too dry. Some farmers manage these individual zones by excluding these problematic areas from the acres cropped. However, variable-rate irrigation technology gives farmers an automated method to vary rates of irrigation water based on the individual management zones within a field (Perry et al. 2015). Using a variable-rate irrigation system can reduce the total irrigation water volume required to grow field crops in two ways: first, producers can exclude non-cropped or marginal areas from water application; and second, producers can lower application rates in low-lying areas or in soils with high water-holding capacity.

Plastic Mulch

Plastic mulch applications for vegetable production provide several adaptations relative to climate change and variability. They reduce water loss to evaporation and minimize leaching of soluble nutrients (e.g., nitrogen) that are applied under the mulch and thus are protected from rainfall-induced leaching. In addition to weed control and minimizing aboveground soil-vegetable contact, plastic mulch also can provide warmer conditions for winter-grown vegetables, although various colors can be used to minimize the degree of heating at a later growth period and attacks from pest insects (e.g. aphids). High tunnels can be used to create a more protected environment for certain crops such as strawberries, to protect from wind and rain damage, to reduce diseases associated with dew formation, and to provide some degree of temperature regulation from day to night, and especially to minimize freeze damage during the winter season. In addition, plastic mulch can help control and prevent soil-borne pathogens and diseases from spreading by providing a shield protecting crops from pests and virus (Katan et al. 1976; Espi et al. 2006).

Drought-Tolerant Crops and Forage

Grasses have varying ability to adjust their growth in response to extreme hydrologic events such as flood and drought, so a careful selection of forage type should be made (Baruch 1994). In particular, prolonged dry periods can reduce the cover and productivity of grasses significantly (Evans et al. 2011; Craine et al. 2013). Thus, the selection of drought-tolerant forages in breeding programs and improvements in grazing management to buffer against drought could aid producers in adapting to more frequent drought conditions under projected climate change. A study found that native grasslands have a wide spectrum of drought tolerance, suggesting that a focused breeding effort including native grasses could lead to an effective adaptation option (Craine et al. 2013). Drought tolerance of high-value vegetable and fruit crops is typically not a breeding objective for Florida because production is irrigated.

Livestock Facility Renovation

Warm air can help reduce winter housing requirements for livestock and additional forage for feed in winter. However, higher temperatures will increase needs for cooling in intensive livestock production systems to reduce potential heat stress resulting in lower productivity in summer (Howden et al. 2007; St-Pierre et al. 2003). Livestock, such as poultry and pigs, kept indoors can be directly affected by increased air temperature. Dairy cattle are susceptible to warm summer temperatures at sunny times of the day during much of the year. Shade structures can reduce livestock heating and minimize a reduction in milk production, fertility, and growth during the warm season. Thus, the renovation—of feedlots and barns, including additional shades, spraying, fanning, air conditioning, circulation, and ventilation—can be a way to adapt to projected warmer temperature, but the efficiency and cost of the cooling system are important considerations (Howden et al. 2007; Armstrong 1994).

Livestock Genomic Selection and Breeding Strategy

Increasing the genetic diversity of livestock can be a strategic approach to reducing climate change impacts on food security. Genetic selection has made significant contributions to the improvement of the feed-to-food conversion efficiency (Herrero et al. 2010; Havenstein et al. 2003). Genetic evaluation and new data collection systems have led to improved genetic selection (Zwald et al. 2004a; Zwald et al. 2004b; VanRaden et al. 2004), and its use will increase in the future (Weigel 2006; Schaeffer 2006; Jonas and de Koning 2015). Genetic selection and crossing with tropical breeds of beef animals could be useful to improve their heat tolerance.

Mixed Crop-Livestock Systems

Mixed crop–livestock systems can be more productive than monoculture systems, as the outcome of one system can be beneficial to another (Rojas-Downing et al. 2017; Thornton and Herrero 2015). Two-thirds of the global population is involved in the mixed agricultural systems, which produce more than half of the livestock and crop products in the world, including meat, milk, cereals, millet, rice, and sorghum(Herrero et al. 2012). Mixed crop-livestock systems have supported increasing food demands in sub-Saharan Africa and South Asia (Thornton and Herrero 2014; Thornton and Herrero 2015). Transition to more efficient livestock systems including mixed crop-livestock could be an effective measure to reduce greenhouse gasses such as thermogenic methane and nitrous oxide, while increasing livestock productivity (Havlík et al. 2014).

Climate Information and Decision Support Systems

Climate information and decision support systems can help agricultural operators develop the capacity to detect expected changes early, respond to the changes quickly, and manage cases appropriately. Thus, they can help reduce production risk, and increase resource use efficiency and the profitability of agricultural operations. Information and decision support systems are not just a compilation of data, but learning tools to develop knowledge-based management plans. Simply providing better climate information and forecasts to potential users will not be enough. Climate information has value only when there is a clearly defined adaptive response and a benefit once the content of the information is considered in the decision-making process (Fraisse et al. 2016). AgroClimate (http://agroclimate.org/) and the conceptual model CISTA-A (Conceptual model using Indicators selected by SysTems thinking for Adaptation strategies for Agro-ecosystems) (Anandhi 2017) are examples of how climate information can be prepared and provided to assist producers and stakeholders in making informed climate-related decisions.

AgroClimate is a web-based climate information and decision support system. The website includes seasonal forecasts, expected impacts of management options for different crops and climate scenarios, and a wide variety of interactive tools that help producers monitor current conditions and plan for the season ahead. AgroClimate has been developed to serve agricultural stakeholders in the southeastern states of Florida, Georgia, Alabama, South Carolina, and North Carolina (Breuer et al. 2009). Users can monitor variables of interest such as growing degree-days, chill hours, disease risks for selected crops, and current and projected drought conditions. Users can also learn about the forecast of climate cycles affecting the Southeastern United States, such as the ENSO phenomenon. Water and carbon footprint calculators can provide estimates of how efficiently water and energy are being used. AgroClimate can assist producers to develop a strategy for a coming season and track current climate conditions affecting crop development and yield. Based on the expected seasonal climate outlook or other climate information, producers are better able to adapt to expected conditions by changing crop selection, planting dates, plant population, cover crop management, livestock management, input purchasing, and nutrient management.

CISTA-A is a decision support tool developed to explore how to adapt ecosystems to climate change using a systems-thinking approach to adaptation (Anandhi 2017). CISTA-A allows users to consider abiotic/biotic information (e.g. temperature, rainfall, and crop yield) and employs ecological, agro-hydrological, and climatological indicators (e.g. length of the growing season, growing degree days, and plant failure temperature) that affect the ecosystem in climate change adaptation planning. The translation of information from indicators to adaptation strategies (incremental systems and transformational adaptation) depends on the degree of change and the level of adaptation. For instance, CISTA-A uses temperature change information to predict spring freezes, and then translates the changes to propose early sowing dates as an adaptation strategy.

Knowledge Gaps and Recommendations for Future Research

Researchers have tried to identify the potential impacts of climate change on the agricultural production system and to develop adaptation and mitigation plans to safely accommodate the changes in the system. However, there are still many knowledge gaps to be filled.

Healthy ecosystems are resistant to external changes and able to quickly recover from damages induced by changes. Thus, maintaining and building healthy ecosystems can help agricultural systems be resilient and sustainable (Tompkins and Adger 2004). Plant and animal biodiversity regulates ecosystem health by controlling hydrological processes, nutrient cycles, and microclimate (Altieri 1999). Some effective ways to improve the ecological resistance and resilience of an agricultural system is to restore its functional biodiversity by rotating crops, using cover crops, intercropping, implementing agroforestry, and mixing crops and livestock (Altieri 1999; Verchot et al. 2007).

Mechanistic crop simulation models (e.g. DSSAT; Jones et al. 2003) have been key tools in extrapolating the impacts of climate variability and change from limited field and controlled-environment experiments to other climatic zones, rainfall regions, soil types, management regimes, crops, and climate change scenarios (Chenu et al. 2017). The impact of individual climate change components and the combined effect of climate change scenarios on crop production and externalities have been explored with such models. However, these models mostly exist for main food grain crops but not for many of the vegetables and fruits grown in Florida. Hence, developing crop models for vegetables and fruit crops based on field experimentation will be critical to assessing the impact of climate change on Florida's agriculture and for preparing adaptation and mitigation strategies. Detailed field experiments investigating the impact of CO_2, temperature, and water supply changes will also be important and are recommended for such needed model development.

Interactive effects of elevated CO_2 with temperature, such as reduction of transpiration canopy cooling as a result of elevated CO_2 and stomata closure, are often not considered in crop models but can, for example, increase pollen sterility in rice (Ziska and Bunce 2007) and sorghum (Prasad et al. 2006). As the frequency of high temperatures (> 32 °C (90 °F)) during the growing season will increase with climate change, the interactions with elevated CO_2 need to be better understood and considered (Attri and Rathore 2003), particularly for crops grown in Florida.

Other interacting effects of climate change on flooding and salinity (Ziska and Bunce 2007) need to be considered but are not yet known, not even for main food crops.

Climate factors often affect crop quality, including protein composition and oil content (Kimball et al. 2001) and various minerals in main food crops (Myers et al. 2014); but less is known about how the nutritional value of vegetables and fruits will be affected by climate change. Field experiments on changes in nutritional contents of vegetables and fruits are needed and should be included in crop models.

Plant breeding technology will help to improve heat tolerance of crops under the projected rising temperatures of climate change (Tester and Langridge 2010). Pollen viability and reproductive fertility of heat-sensitive crops (such as tomatoes and snap beans) are limited at high temperatures, but there may be a potential to improve this genetically (Bita and Gerats 2013). It will be important to improve drought tolerance of crops under projected increases in air temperature and with changes in rainfall, particularly for those crops that are typically rainfed, such as peanuts, cotton, maize, and tropical grasses. Factors influencing the genetics of crop diseases have been recently discovered, and specific genetics can be selected for (Bishop and Woolliams 2014; Stear et al. 2001). Genetic selection for disease resistance traits in animals can allow farmers to raise livestock in less preferable climates (Berry et al. 2011). A better understanding of disease pressure under climate change and the ability to breed for improved disease resistance in livestock will be important for adaptation of livestock to climate change.

Florida's growers are part of a global market, and production in competing regions will also be affected by climate change. Not only will Florida's growers be adapting to climate changes, they will also be competing against growers elsewhere making their own adaptations. When considering the economic prospects for example for Florida's citrus and tomato growers in the coming decades, climate change in Florida needs to be considered, but one must also consider climate change and potential adaptations in main competing regions within the US and other countries like Brazil and Mexico.

As population increases in Florida are likely to continue, urban sprawl and demands for water from municipal, energy, and other sectors will increasingly conflict with agricultural irrigation requirements. Policy research will be essential to balance these competing demands for land and water resources. This research should evaluate agricultural competitiveness in Florida, both for its ability to meet food, fiber, and fuel needs of the region as well as to contribute to national and global food, fiber, and fuel production (Marcus and Kiebzak 2008).

Initial research has shown that there is a strong interaction between changes in agricultural land use/land cover and regional climate, a feedback often overlooked and less understood (Shin and Baigorria 2012). Traditional agricultural research has followed a linear approach, from research scientists to extension agents to farmers. To address the complex issues of sustainability in the face of changing and variable climate, research must follow a new paradigm—one that emphasizes the integration of research, teaching, and extension, invites the participation of decision-makers throughout the research process, and assembles the diverse elements of agriculture through a systems approach (Breuer et al. 2009, 2010; Bartels et al. 2012; Roncoli 2006). Crop and livestock breeding and management research are important elements to the overall agricultural research portfolio, but they should be incorporated into integrated approaches to ensure that they contribute to agricultural sustainability.

While researchers are already working with farmers in Florida to develop and assess technologies to mitigate and adapt to climate variability and change, additional research is needed to identify and incorporate adaptive technologies into agricultural systems. Analysis of these technologies should include carbon, energy, water, and nutrient balances as well as life cycle, risk and economic analysis (a systems analysis that is only rarely applied to agricultural research and development).

Agriculture and food production systems are complex and associated with many fields of science including agronomy, biology, crop physiology, soil science, economics, sociology, mathematics, physics, and environmental sciences. Thus, solutions to an agricultural challenge will be multidisciplinary, requiring holistic views and approaches from emerging scientific platforms such as biotechnology, nanotechnology, information science, and cognitive science (Scott et al. 2016; Conway 2012). Recent advances in data and network sciences, sensing and robotics technology, and computing resources are expected to enhance informed decision-making in agriculture by promoting the accurate and quick exchange of information among farmers, researchers, and tool/equipment manufacturers, and by improving precision agriculture and smart farming technology.

Florida's agriculture has a long history of successful adaptations to the vagaries of weather and climate. However, climate change poses a challenge that is unprecedented in its magnitude and pace of onset. As with any major change in global agricultural markets, the winners will be those who are able, with the help of their government and industrial leaders, to cope with these challenges and to recognize and take advantage of opportunities.

Acknowledgments

Carolyn Cox, Florida Climate Institute Coordinator, is recognized for her role in coordinating this chapter.

References

Adams, R. M., C. Rosenzweig, R. Peart, J. T. Ritchie, and B. A. McCarl (1990), Global climate change and US agriculture, Nature, 345(6272), 219.

Allen Jr, L., and K. Boote (2000), Crop ecosystem responses to climatic change: soybean, In Climate Change and Global Crop Productivity, pp. 133-160, University of Florida, Gainesville, FL.

Allen, L. H., V. G. Kakani, J. C. Vu, and K. J. Boote (2011), Elevated CO 2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum, Journal of Plant Physiology, 168(16), 1909-1918.

Allen, L., D. Pan, K. Boote, N. Pickering, and J. Jones (2003), Carbon dioxide and temperature effects on evapotranspiration and water use efficiency of soybean, Agronomy Journal, 95(4), 1071-1081.

Altieri, M. A. (1999), The ecological role of biodiversity in agroecosystems, Agriculture, Ecosystems and Environment, 74(1), 19-31.

Anandhi, A. (2017), CISTA-A: Conceptual model using indicators selected by systems thinking for adaptation strategies in a changing climate: Case study in agro-ecosystems, Ecological Modelling, 345, 41-55.

Anderson, S. A. (1990), Core indicators of nutritional state for difficult-to-sample populations, The Journal of Nutrition.

Anyamba, A., J. L. Small, S. C. Britch, C. J. Tucker, E. W. Pak, C. A. Reynolds, J. Crutchfield, and K. J. Linthicum (2014), Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns, PLoS One, 9(3), e92538.

Armstrong, D. (1994), Heat stress interaction with shade and cooling, Journal of Dairy Science, 77(7), 2044-2050.

Attri, S., and L. Rathore (2003), Simulation of impact of projected climate change on wheat in India, International Journal of Climatology, 23(6), 693-705.

Backlund, P., A. Janetos, and D. Schimel (2008), The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. U.S. Climate Change Science Program: Synthesis and Assessment Product 4.3, Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.

Backlund, P., A. Janetos, and D. Schimel (2009), The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, Nova Science Publishers, Inc., New York.

Baker, J. T., K. J. Boote, and L. H. Allen (1995), Potential climate change effects on rice: Carbon dioxide and temperature, in Climate Change and Agriculture: Analysis of Potential International Impacts, pp. 31-47, Amerian Society of Agronomy.

Baker, J., L. Allen, and K. Boote (1990), Growth and yield responses of rice to carbon dioxide concentration, The Journal of Agricultural Science, 115(03), 313-320.

Baker, J., L. Allen, and K. Boote (1992), Response of rice to carbon dioxide and temperature, Agricultural and Forest Meteorology, 60(3-4), 153-166.

Balkcom, K., L. Duzy, D. Dourte, C. Fraisse (2012), Conservation Tillage: Agricultural Management Options for Climate Variability and Change. Available: http://agroclimate.org/wp-content/uploads/2016/03/Conservation-tillage.pdf.

Bartels, W., C. Furman, F. Royce, B. Ortiz, D. Zierden, and C. Fraisse (2012), Developing a learning community: Lessons from a climate working group for agriculture in the Southeast USA, Southeast Climate Consortium Technical Report Series, 12-002.

Baruch, Z. (1994), Responses to drought and flooding in tropical forage grasses, Plant and Soil, 164(1), 87-96.

Benedictos Jr, P., and N. Yavari (1997), Optimum sowing date in relation to flower drop reduction in tomato, paper presented at VIII International Symposium on Timing Field Production in Vegetable Crops, ISHS Acta Horticulturae 533.

Bernabucci, U., N. Lacetera, L. Basiricò, B. Ronchi, P. Morera, E. Serene, and A. Nardone (2006), Hot season and BCS affect leptin secretion of periparturient dairy cows, paper presented at Journal of Animal Science, Amer Soc Animal Science 1111 North Dunlap Ave, Savoy, IL 61874 USA.

Bernacchi, C. J., B. A. Kimball, D. R. Quarles, S. P. Long, and D. R. Ort (2007), Decreases in stomatal conductance of soybean under open-air elevation of CO2 are closely coupled with decreases in ecosystem evapotranspiration, Plant Physiology, 143(1), 134-144.

Berry, D. P., M. L. Bermingham, M. Good, and S. J. More (2011), Genetics of animal health and disease in cattle, Irish Veterinary Journal, 64(1), 5.

Biasutti, M., A. H. Sobel, S. J. Camargo, and T. T. Creyts (2012), Projected changes in the physical climate of the Gulf Coast and Caribbean, Climatic Change, 112(3-4), 819-845.

Bishop, S. C., and J. A. Woolliams (2014), Genomics and disease resistance studies in livestock, Livestock Science, 166, 190-198.

Bita, C. E., and T. Gerats (2013), Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops, Frontiers in Plant Science, 4.

Blanco, R. I., G. M. Naja, R. G. Rivero, and R. M. Price (2013), Spatial and temporal changes in groundwater salinity in South Florida, Applied Geochemistry, 38, 48-58.

Bloom, A. J., M. Burger, J. S. R. Asensio, and A. B. Cousins (2010), Carbon dioxide enrichment inhibits nitrate assimilation in wheat and Arabidopsis, Science, 328(5980), 899-903.

Boote, K. J., L. H. Allen Jr, P. V. Prasad, and J. W. Jones (2010), Testing effects of climate change in crop models, in Handbook of Climate Change and Agroecosystems, pp. 109-129, Imperial College Press, London.

Boote, K. J., L. H. Allen, P. V. Prasad, J. T. Baker, R. W. Gesch, A. M. Snyder, P. Deyun, and J. M. Thomas (2005), Elevated temperature and CO2 impacts on pollination, reproductive growth, and yield of several globally important crops, Journal of Agricultural Meteorology, 60(5), 469-474.

Breuer, N. E., C. W. Fraisse, and P. E. Hildebrand (2009), Molding the pipeline into a loop: the participatory process of developing AgroClimate, a decision support system for climate risk reduction in agriculture, Journal of Service Climatology, 3(1), 1-12.

Campbell, C. A. (1994), Handling of Florida-grown and imported tropical fruits and vegetables, HortScience, 29(9), 975-978.

Chenu, K., J. R. Porter, P. Martre, B. Basso, S. C. Chapman, F. Ewert, M. Bindi, and S. Asseng (2017), Contribution of crop models to adaptation in wheat, Trends in Plant Science, 22(6), 472-490.

Chun, J. A., Q. Wang, D. Timlin, D. Fleisher, and V. R. Reddy (2011), Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn, Agricultural and Forest Meteorology, 151(3), 378-384.

Conway, G. (2012), One billion hungry: can we feed the world?, Cornell University Press, Ithaca, NY.

Craine, J. M., T. W. Ocheltree, J. B. Nippert, E. G. Towne, A. M. Skibbe, S. W. Kembel, and J. E. Fargione (2013), Global diversity of drought tolerance and grassland climate-change resilience, Nature Climate Change, 3(1), 63-67.

Das, R., L. Sailo, N. Verma, P. Bharti, and J. Saikia (2016), Impact of heat stress on health and performance of dairy animals: A review, Veterinary World, 9(3), 260.

Day, J. F., and J. Shaman (2008), Using hydrologic conditions to forecast the risk of focal and epidemic arboviral transmission in peninsular Florida, Journal of Medical Entomology, 45(3), 458-465.

De Rensis, F., and R. J. Scaramuzzi (2003), Heat stress and seasonal effects on reproduction in the dairy cow—a review, Theriogenology, 60(6), 1139-1151.

Ebrahim, M. K., O. Zingsheim, M. N. El-Shourbagy, P. H. Moore, and E. Komor (1998), Growth and sugar storage in sugarcane grown at temperatures below and above optimum, Journal of Plant Physiology, 153(5-6), 593-602.

EPA, (1997), Climate Change and Florida. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi/40000IY6.PDF?Dockey=40000IY6.PDF.

Espi, E., A. Salmeron, A. Fontecha, Y. García, and A. Real (2006), Plastic films for agricultural applications, Journal of Plastic Film and Sheeting, 22(2), 85-102.

Evans, S. E., K. M. Byrne, W. K. Lauenroth, and I. C. Burke (2011), Defining the limit to resistance in a drought-tolerant grassland: long-term severe drought significantly reduces the dominant species and increases ruderals, Journal of Ecology, 99(6), 1500-1507.

FDACS (2016), Florida Statewide Agricultural Irrigation Demand (FSAID). Available: http://freshfromflorida.s3.amazonaws.com/Media%2FFiles%2FAgricultural-Water-Policy-Files%2FAgricultural-Water-Supply-Planning%2FFSAID+II+Final+Report_The+Balmoral+Group_08.31.2015_Corr.1.pdf.

Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, and M. D. Mastrandrea (2014), Climate Change 2014: Impacts, Adaptation, and Vulnerability, in Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Fraisse, C. W., N. E. Breuer, D. Zierden, and K. T. Ingram (2009), From climate variability to climate change: Challenges and opportunities to extension, Journal of Extension, 47(2), 2FEA9.

Fraisse, C., J. H. Andreis, T. Borba, , V. Cerbar, E. Gelcer, W. Pavan, D. Pequeno, D. Perondi, X. Shen, C. Staub, and O. Uryasev (2016), AgroClimate - Tools for managing climate risk in agriculture, Agrometeoros Journal, 24(1), 121-129.

Fritschi, F. B., K. J. Boote, L. Sollenberger, and L. Hartwell (1999), Carbon dioxide and temperature effects on forage establishment: tissue composition and nutritive value, Global Change Biology, 5(7), 743-753.

Gao, Y., J. Fu, J. Drake, Y. Liu, and J. Lamarque (2012), Projected changes of extreme weather events in the eastern United States based on a high resolution climate modeling system, Environmental Research Letters, 7(4), 044025.

Ghannoum, O., S. v. Caemmerer, L. Ziska, and J. P. Conroy (2000), The growth response of C4 plants to rising atmospheric CO2 partial pressure: a reassessment, Plant, Cell & Environment, 23(9), 931-942.

Hahn, G. (1999), Dynamic responses of cattle to thermal heat loads, Journal of Animal Science, 77, 10-20.

Hansen, J. W., A. W. Hodges, and J. W. Jones (1998), ENSO influences on agriculture in the southeastern United States, Journal of Climate, 11(3), 404-411.

Hansen, J. W., J. W. Jones, C. F. Kiker, and A. W. Hodges (1999), El Niño–Southern Oscillation impacts on winter vegetable production in Florida, Journal of Climate, 12(1), 92-102.

Hansen, P. (2007), Exploitation of genetic and physiological determinants of embryonic resistance to elevated temperature to improve embryonic survival in dairy cattle during heat stress, Theriogenology, 68, S242-S249.

Havenstein, G., P. Ferket, and M. Qureshi (2003), Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets, Poultry Science, 82(10), 1500-1508.

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Böttcher, and R. T. Conant (2014), Climate change mitigation through livestock system transitions, Proceedings of the National Academy of Sciences, 111(10), 3709-3714.

Heimlich, B., and F. Bloetscher (2011), Effects of sea level rise and other climate change impacts on southeast Florida's water resources, Florida Water Resources Journal, 63(9), 37-48.

Herrero, M., P. K. Thornton, A. M. Notenbaert, S. Wood, S. Msangi, H. Freeman, D. Bossio, J. Dixon, M. Peters, and J. van de Steeg (2010), Smart investments in sustainable food production: revisiting mixed crop-livestock systems, Science, 327(5967), 822-825.

Herrero, M., P. K. Thornton, A. M. O. Notenbaert, S. Msangi, S. Wood, R. Kruska, J. A. Dixon, D. A. Bossio, J. Van de Steeg, and H. A. Freeman (2012), Drivers of change in crop–livestock systems and their potential impacts on agro-ecosystems services and human wellbeing to 2030: A study commissioned by the CGIAR Systemwide Livestock Programme.

Howden, S. M., J.-F. Soussana, F. N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke (2007), Adapting agriculture to climate change, Proceedings of the National Academy of Sciences, 104(50), 19691-19696.

IPCC (2007), Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland.

Joel Love, J. D., Kirk Brock, Daniel Dourte, Clyde Fraisse (2015), High-Residue Cover Crops A Management Option for Climate Variability and Change. Available: http://agroclimate.org/wp-content/uploads/2016/03/High-residue-cover-crops.pdf.

Johnson, T., J. Butcher, D. Deb, M. Faizullabhoy, P. Hummel, J. Kittle, S. McGinnis, L. Mearns, D. Nover, and A. Parker (2015), Modeling streamflow and water quality sensitivity to climate change and urban development in 20 US watersheds, Journal of the American Water Resources Association, 51(5), 1321-1341.

Jonas, E., and D. J. de Koning (2015), Genomic selection needs to be carefully assessed to meet specific requirements in livestock breeding programs, Frontiers in Genetics, 6, 49.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman, and J. T. Ritchie (2003), The DSSAT cropping system model, European Journal of Agronomy, 18(3), 235-265.

Karl, T. R. (2009), Global Climate Change Impacts in the United States, Cambridge University Press, Cambridge, UK.

Katan, J., A. Greenberger, H. Alon, and A. Grinstein (1976), Solar heating by polyethylene mulching for the control of diseases caused by soil-borne pathogens, Phytopathology, 66(5), 683-688.

Ketabchi, H., D. Mahmoodzadeh, B. Ataie-Ashtiani, and C. T. Simmons (2016), Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration, Journal of Hydrology, 535, 235-255.

Kimball, B. A., P. J. PINTER, R. L. Garcia, R. L. LaMORTE, G. W. Wall, D. J. Hunsaker, G. Wechsung, and F. Wechsung (1995), Productivity and water use of wheat under free-air CO2 enrichment, Global Change Biology, 1(6), 429-442.

Kimball, B., C. Morris, P. Pinter, G. Wall, D. Hunsaker, F. Adamsen, R. LaMorte, S. Leavitt, T. Thompson, and A. Matthias (2001), Elevated CO2, drought and soil nitrogen effects on wheat grain quality, New Phytologist, 150(2), 295-303.

Kimball, B., K. Kobayashi, and M. Bindi (2002), Responses of agricultural crops to free-air CO 2 enrichment, Advances in agronomy, 77, 293-368.

King, K., and D. Greer (1986), Effects of carbon dioxide enrichment and soil water on maize, Agronomy Journal, 78(3), 515-521.

Klassen, W., C. F. Brodel, and D. A. Fieselmann (2002), Exotic pests of plants: current and future threats to horticultural production and trade in Florida and the Caribbean Basin, Micronesica Supplement, 6, 5-27.

Kunavongkrit, A., A. Suriyasomboon, N. Lundeheim, T. W. Heard, and S. Einarsson (2005), Management and sperm production of boars under differing environmental conditions, Theriogenology, 63(2), 657-667.

Kurukulasuriya, P., and S. Rosenthal (2003), Climate change and agriculture: A review of impacts and adaptations world bank climate change series paper no. 91, 106 pp., The International Bank for Reconstruction and Development / The World Bank, Washington, D.C.

Lamm, F. R., P. D. Colaizzi, J. P. Bordovsky, T. P. Trooien, J. Enciso-Medina, D. O. Porter, D. H. Rogers, and D. M. O'Brien (2010), Can Subsurface Drip Irrigation (SDI) be a Competitive Irrigation System in the Great Plains Region for Commodity Crops?, paper presented at 5th National Decennial Irrigation Conference Proceedings, 5-8 December 2010, Phoenix Convention Center, Phoenix, Arizona USA, American Society of Agricultural and Biological Engineers.

Leakey, A. D., M. Uribelarrea, E. A. Ainsworth, S. L. Naidu, A. Rogers, D. R. Ort, and S. P. Long (2006), Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO2 concentration in the absence of drought, Plant Physiology, 140(2), 779-790.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor (2008), Prioritizing climate change adaptation needs for food security in 2030, Science, 319(5863), 607-610.

Mader, T., and M. Davis (2004), Effect of management strategies on reducing heat stress of feedlot cattle: feed and water intake, Journal of Animal Science, 82(10), 3077-3087.

Manderscheid, R., M. Erbs, and H.-J. Weigel (2014), Interactive effects of free-air CO 2 enrichment and drought stress on maize growth, European Journal of Agronomy, 52, 11-21.

Marcus, R. R., and S. Kiebzak (2008), The role of water doctrines in enhancing opportunities for sustainable agriculture in Alabama, Journal of the American Water Resources Association, 44(6), 1578-1590.

Marella, R. L. (1999), Water withdrawals, use, discharge, and trends in Florida, 1995, Geological Survey, Water Resources Div., Tallahassee, FL (United States); Florida State Dept. of Environmental Protection, Tallahassee, FL.

Maul, G. A., and D. M. Martin (1993), Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record?, Geophysical Research Letters, 20(18), 1955-1958.

Mendelsohn, R., A. Dinar, and L. Williams (2006), The distributional impact of climate change on rich and poor countries, Environment and Development Economics, 11(02), 159-178.

Miller, K. A., and M. H. Glantz (1988), Climate and economic competitiveness: Florida freezes and the global citrus processing industry, Climatic Change, 12(2), 135-164.

Misra, V., E. Carlson, R. Craig, D. Enfield, B. Kirtman, W. Landing, S. Lee, D. Letson, F. Marks, and J. Obeysekera (2011), Climate scenarios: a Florida-centric view. Florida Climate Change Task Force, Center for Ocean-Atmospheric Prediction Studies, 14, 1-61.

Mitlöhner, F., J. Morrow, J. Dailey, S. Wilson, M. Galyean, M. Miller, and J. McGlone (2001), Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle, Journal of Animal Science, 79(9), 2327-2335.

Morison, J. I. (1987), Intercellular C02 Concentration and Stomatal Response to C02 James I. L Morison, in Stomatal Function, edited by E. Zeiger, G. D. Farquhar and I. R. Cowan, p. 229, Stanford University Press, Stanford, CA.

Morton, J. F. (1987), Fruits of warm climates, Julia F. Morton, Miami, FL.

Myers, S. S., A. Zanobetti, I. Kloog, P. Huybers, A. D. Leakey, A. Bloom, E. Carlisle, L. H. Dietterich, G. Fitzgerald, and T. Hasegawa (2014), Rising CO2 threatens human nutrition, Nature, 510(7503), 139.

Nardone, A., B. Ronchi, N. Lacetera, M. S. Ranieri, and U. Bernabucci (2010), Effects of climate changes on animal production and sustainability of livestock systems, Livestock Science, 130(1), 57-69.

National Academies of Sciences, E., Medicine (2016), Attribution of extreme weather events in the context of climate change, National Academies Press.

National Climate Assessment (2014), Available: http://nca2014.globalchange.gov/.

Newman, Y. C., L. E. Sollenberger, K. J. Boote, L. H. Allen, J. M. Thomas, and R. C. Littell (2006), Nitrogen fertilization affects bahiagrass responses to elevated atmospheric carbon dioxide, Agronomy Journal, 98(2), 382-387.

Newman, Y., L. Sollenberger, K. Boote, L. Allen, and R. Littell (2001), Carbon dioxide and temperature effects on forage dry matter production, Crop Science, 41(2), 399-406.

NHC (2017), Hurricanes in History. Available: http://www.nhc.noaa.gov/outreach/history/.
Nicholls, R. J., and A. Cazenave (2010), Sea-level rise and its impact on coastal zones, Science, 328(5985), 1517-1520.
NOAA (2017a), National Centers for Environmental Information - Data Tools: 1981 - 2010 Normals.
NOAA (2017b), Global Greenhouse Gas Reference Network, Earth System Research Laboratory - Global Monitoring Division.
Obeysekera, J., J. Park, M. Irizarry-Ortiz, P. Trimble, J. Barnes, J. VanArman, W. Said, and E. Gadzinski (2011), Past and Projected Trends in Climate and Sea Level for South Florida, South Florida Water Management District, West Palm Beach, FL.
Ottman, M. J., B. Kimball, P. Pinter, G. Wall, R. Vanderlip, S. Leavitt, R. LaMorte, A. Matthias, and T. Brooks (2001), Elevated CO2 increases sorghum biomass under drought conditions, New Phytologist, 150(2), 261-273.
Pachauri, R. K., M. R. Allen, V. R. Barros, J. Broome, W. Cramer, R. Christ, J. A. Church, L. Clarke, Q. Dahe, and P. Dasgupta (2014), Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, IPCC.
Pan, D. (1996), Soybean responses to elevated temperature and doubled CO_2, University of Florida, Gainesville, FL.
Peel, M. C., B. L. Finlayson, and T. A. McMahon (2007), Updated world map of the Köppen-Geiger climate classification, Hydrology and Earth System Sciences, 4(2), 439-473.
Perry, C., C. W. Fraisse, and D. Dourte (2015), Variable-Rate Irrigation: A Management Option for Climate Variability and Change. Available: http://agroclimate.org/wpcontent/uploads/2016/03/Variable-rate-irrigation.pdf.
Polley, H. W., D. D. Briske, J. A. Morgan, K. Wolter, D. W. Bailey, and J. R. Brown (2013), Climate change and North American rangelands: trends, projections, and implications, Rangeland Ecology & Management, 66(5), 493-511.
Prasad, P. V., K. J. Boote, and L. H. Allen (2006), Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures, Agricultural and Forest Meteorology, 139(3), 237-251.
Prasad, P., K. J. Boote, L. H. Allen, and J. M. Thomas (2002), Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (Phaseolus vulgaris L.), Global Change Biology, 8(8), 710-721.
Prasad, V. P., K. J. Boote, L. Hartwell Allen, and J. M. Thomas (2003), Super-optimal temperatures are detrimental to peanut (Arachis hypogaea L.) reproductive processes and yield at both ambient and elevated carbon dioxide, Global Change Biology, 9(12), 1775-1787.
Prinos, S. T. (2016), Saltwater intrusion monitoring in Florida, Florida Scientist, 79, 4.
Putnam, A. (2011), Florida Agriculture: By the Numbers., Florida Department of Agriculture and Consumer Services, Tallahassee, FL.
Putnam, A. (2015a), Florida Agriculture: By the Numbers., Florida Department of Agriculture and Consumer Services, Tallahassee, FL.
Putnam, A. (2015b), Florida Agriculture Overview and Statistics.
Putnam, A. (2015c), 2015 Annual Report., Florida Department of Agriculture and Consumer Services, Tallahassee, FL.
Reddy, K. R., H. F. Hodges, and B. A. Kimball (2000), Crop ecosystem responses to climatic change: Cotton, in Climate Change and Global Crop Productivity, edited by K. R. Reddy and H. F. Hodges, pp. 161-187, CABI Publishing, Oxon, UK.
Regan, K. E. (2003), Balancing public water supply and adverse environmental impacts under Florida water law: from water wars towards adaptive management, Journal of Land Use & Environmental Law, 19(1), 123-184.
Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, and J. Jones (2003), US agriculture and climate change: new results, Climatic Change, 57(1), 43-67.
Reynolds, C., L. Crompton, and J. Mills (2010), Livestock and climate change impacts in the developing world, Outlook on Agriculture, 39(4), 245-248.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan, and S. A. Woznicki (2017), Climate change and livestock: impacts, adaptation, and mitigation, Climate Risk Management, 16, 145-163.

Roncoli, C. (2006), Ethnographic and participatory approaches to research on farmers' responses to climate predictions, Climate Research, 33(1), 81-99.
Rosenzweig, C., and D. Hillel (1998), Climate Change and the Global Harvest, Oxford University Press, New York.
Rowland, D. L., W. H. Faircloth, P. Payton, D. T. Tissue, J. A. Ferrell, R. B. Sorensen, and C. L. Butts (2012), Primed acclimation of cultivated peanut (Arachis hypogaea L.) through the use of deficit irrigation timed to crop developmental periods, Agricultural Water Management, 113, 85-95.
Sallenger Jr, A. H., K. S. Doran, and P. A. Howd (2012), Hotspot of accelerated sea-level rise on the Atlantic coast of North America, Nature Climate Change, 2(12), 884-888.
Sato, S., M. Peet, and J. Thomas (2000), Physiological factors limit fruit set of tomato (Lycopersicon esculentum Mill.) under chronic, mild heat stress, Plant, Cell & Environment, 23(7), 719-726.
Scavia, D., J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, and C. Mason (2002), Climate change impacts on US coastal and marine ecosystems, Estuaries, 25(2), 149-164.
Schaeffer, L. (2006), Strategy for applying genome-wide selection in dairy cattle, Journal of animal Breeding and genetics, 123(4), 218-223.
Schmidt, C. W. (2000), Lessons from the flood: will Floyd change livestock farming?, Environmental Health Perspectives, 108(2), A74.
Scott, N. R., H. Chen, and R. Schoen (2016), Sustainable global food supply, Handbook of science and technology convergence. Springer International, Switzerland.
Shaman, J., J. F. Day, and M. Stieglitz (2005), Drought-induced amplification and epidemic transmission of West Nile virus in southern Florida, Journal of Medical Entomology, 42(2), 134-141.
Shin, D., and G. A. Baigorria (2012), Potential influence of land development patterns on regional climate: a summer case study in the Central Florida, Natural hazards, 62(3), 877-885.
Sionit, N., D. Mortensen, B. Strain, and H. Hellmers (1981), Growth response of wheat to CO2 enrichment and different levels of mineral nutrition, Agronomy Journal, 73(6), 1023-1027.
Sleep, D., and R. Gitzen (2015), Fresh from Florida, 2015 International Report, Available: http://www.freshfromflorida.com/content/download/59882/1184512/2015_International_Report.pdf.
Stear, M., S. Bishop, B. Mallard, and H. Raadsma (2001), The sustainability, feasibility and desirability of breeding livestock for disease resistance, Research in Veterinary Science, 71(1), 1-7.
Stephenson, D. S. (2000), The tri-state compact: falling waters and fading opportunities, Journal of Land Use and Environmental Law, 16, 83.
St-Pierre, N., B. Cobanov, and G. Schnitkey (2003), Economic losses from heat stress by US livestock industries, Journal of Dairy Science, 86, 52-77.
Sweet, W. V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E. R. Thieler, and C. Zervas (2017), Global and Regional Sea Level Rise Scenarios for the United StatesRep., National Oceanic and Atmospheric Administration, Silver Spring, Maryland.
Tankson, J., Y. Vizzier-Thaxton, J. Thaxton, J. May, and J. Cameron (2001), Stress and nutritional quality of broilers, Poultry Science, 80(9), 1384-1389.
Tester, M., and P. Langridge (2010), Breeding technologies to increase crop production in a changing world, Science, 327(5967), 818-822.
Thornton, P. K. (2010), Livestock production: recent trends, future prospects, Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2853-2867.
Thornton, P. K., and M. Herrero (2014), Climate change adaptation in mixed crop–livestock systems in developing countries, Global Food Security, 3(2), 99-107.
Thornton, P. K., and M. Herrero (2015), Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa, Nature Climate Change, 5(9), 830-836.
Thornton, P. K., J. Van de Steeg, A. Notenbaert, and M. Herrero (2009), The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know, Agricultural Systems, 101(3), 113-127.
Todd, M. J., R. Muneepeerakul, F. Miralles-Wilhelm, A. Rinaldo, and I. Rodriguez-Iturbe (2012), Possible climate change impacts on the hydrological and vegetative character of Everglades National Park, Florida, Ecohydrology, 5(3), 326-336.
Tompkins, E., and W. N. Adger (2004), Does adaptive management of natural resources enhance resilience to climate change?, Ecology and Society, 9(2), 10.

Trimble, P., E. Santee, and C. Neidrauer (1998), Preliminary estimate of impacts of sea-level rise on the regional water resources of southeastern Florida, Journal of Coastal Research, 252-255.

Tripp, K. E., M. M. Peet, D. M. Pharr, D. H. Willits, and P. V. Nelson (1991), CO2-enhanced yield and foliar deformation among tomato genotypes in elevated CO2 environments, Plant Physiology, 96(3), 713-719.

Tubiello, F., C. Rosenzweig, R. Goldberg, S. Jagtap, and J. Jones (2002), Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: Wheat, potato, maize, and citrus, Climate Research, 20(3), 259-270.

Twine, T. E., J. J. Bryant, K. T Richter, C. J. Bernacchi, K. D. McConnaughay, S. J. Morris, and A. D. Leakey (2013), Impacts of elevated CO2 concentration on the productivity and surface energy budget of the soybean and maize agroecosystem in the Midwest USA, Global Change Biology, 19(9), 2838-2852.

USDA-NASS (2012), 2012 Census of Agriculture Vol. 1, Ch. 1: State Level Data, Florida.

USDA-NASS (2016), Cropland Data Layer, Available: https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php.

USDA-NASS (2017), 2016 State Agriculture Overview, Available: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=FLORIDA.

VanRaden, P., A. Sanders, M. Tooker, R. Miller, H. Norman, M. Kuhn, and G. Wiggans (2004), Development of a national genetic evaluation for cow fertility, Journal of Dairy Science, 87(7), 2285-2292.

Verchot, L. V., M. Van Noordwijk, S. Kandji, T. Tomich, C. Ong, A. Albrecht, J. Mackensen, C. Bantilan, K. Anupama, and C. Palm (2007), Climate change: linking adaptation and mitigation through agroforestry, Mitigation and Adaptation Strategies for Global Change, 12(5), 901-918.

Von Lehe, A. (2007), Climate Change and South Carolina's Economy, Southeastern Environmental Law Journal, 16, 359.

Walthall, C., J. Hatfield, E. Marshall, L. Lengnick, P. Backlund, S. Adkins, E. Ainsworth, F. Booker, D. Blumenthal, and J. Bunce (2013), Climate Change and Agriculture in the United States: Effects and Adaptation, USDA, Washington, D.C., Available: https://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf.

Wang, D., S. C. Hagen, and K. Alizad (2013), Climate change impact and uncertainty analysis of extreme rainfall events in the Apalachicola River basin, Florida, Journal of Hydrology, 480, 125-135.

Weigel, K. A. (2006), Prospects for improving reproductive performance through genetic selection, Animal reproduction science, 96(3), 323-330.

Whitehead, P., R. Wilby, R. Battarbee, M. Kernan, and A. J. Wade (2009), A review of the potential impacts of climate change on surface water quality, Hydrological Sciences Journal, 54(1), 101-123.

Wright, D., J. Marois, C. Fraisse, and D. Dourte (2015), Agricultural Management Options for Climate Variability and Change: Sod-Based Rotation, EDIS, UF/IFAS(AE49200).

Zervas, C. (2009), Sea level variations of the United States., National Oceanic and Atmospheric Administration, Silver Spring, MD.

Zhang, K. (2011), Analysis of non-linear inundation from sea-level rise using LIDAR data: a case study for South Florida, Climatic Change, 106(4), 537-565.

Zhao, D., D. Wright, J. Marois, C. Mackowiak, and T. Katsvairo (2008), Yield and water use efficiency of cotton and peanut in conventional and sod-based cropping systems, paper presented at Proc. 30th Southern Conserv. Agric. Syst. Conf. and 8th Ann. Georgia Conserv. Prod. Syst. Trng. Conf., Tifton, Georgia.

Ziska, L. H., and J. A. Bunce (2007), Predicting the impact of changing CO2 on crop yields: some thoughts on food, New Phytologist, 175(4), 607-618.

Zotarelli, L., C. Fraisse, and D. Dourte (2015), Agricultural Management Options for Climate Variability and Change: Microirrigation, EDIS, UF/IFAS(HS1203).

Zwald, N., K. Weigel, Y. Chang, R. Welper, and J. Clay (2004a), Genetic selection for health traits using producer-recorded data. I. Incidence rates, heritability estimates, and sire breeding values, Journal of dairy science, 87(12), 4287-4294.

Zwald, N., K. Weigel, Y. Chang, R. Welper, and J. Clay (2004b), Genetic selection for health traits using producer-recorded data. II. Genetic correlations, disease probabilities, and relationships with existing traits, Journal of dairy science, 87(12), 4295-4302.